High Energy Density Physics Experiments with Terawatt to Petawatt Ultrafast, High Intensity Lasers

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I will discuss various approaches to the creation and study of high density plasmas with high intensity lasers

I. A few words about the state of high intensity laser technology

- State of the art in table top lasers
- Petawatt lasers

II. High energy density physics by isochoric heating of solids

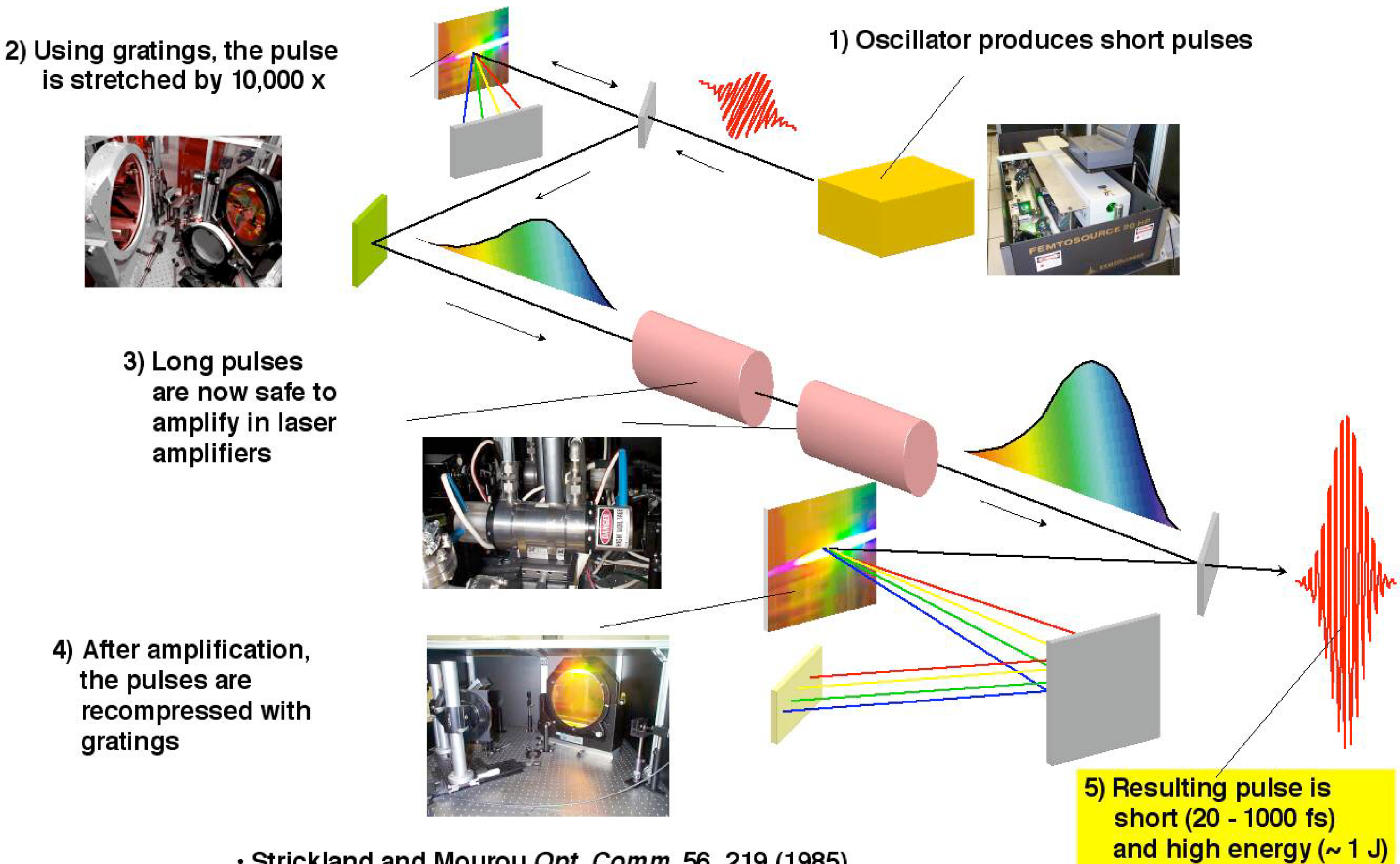
- Isochoric heating and probing of off-Hugoniot equations of state
- Advantages and challenges
- Isochoric heating with ultrafast laser produced x-ray pulses
- Isochoric heating with laser produced MeV protons

III. Explosions of laser heated clusters

- Physics of clusters subject to intense femtosecond laser irradiation
- Explosion mechanisms: Hydro vs Coulomb explosion
- Fast Ion ejection from exploding clusters
- Anisotropy in the ejection of ions

IV. Concluding remarks

Most modern ultraintense lasers are based on Chirped Pulse Amplification



• Strickland and Mourou *Opt. Comm.* 56, 219 (1985)

The current state-of-the-art ultrafast, ultraintense lasers (UULs) tends to fall into two categories

<u>Table top terawatt lasers:</u>

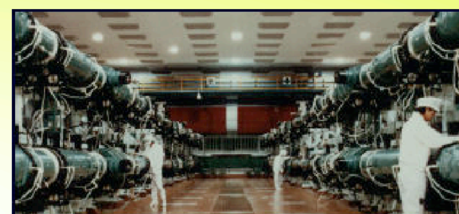
Pulse energy ~ .001 - 1 J,
Pulse duration <100 fs,
Peak Power < 100 TW
Repetition Rate ~ 1 kHz - 10 Hz

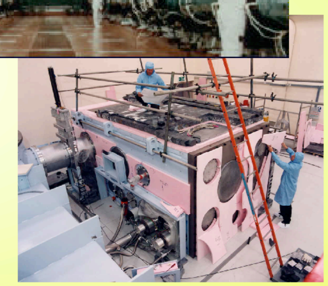
Usually Ti:sapphire based

<u>Large scale multi- terawatt to petawatt</u>

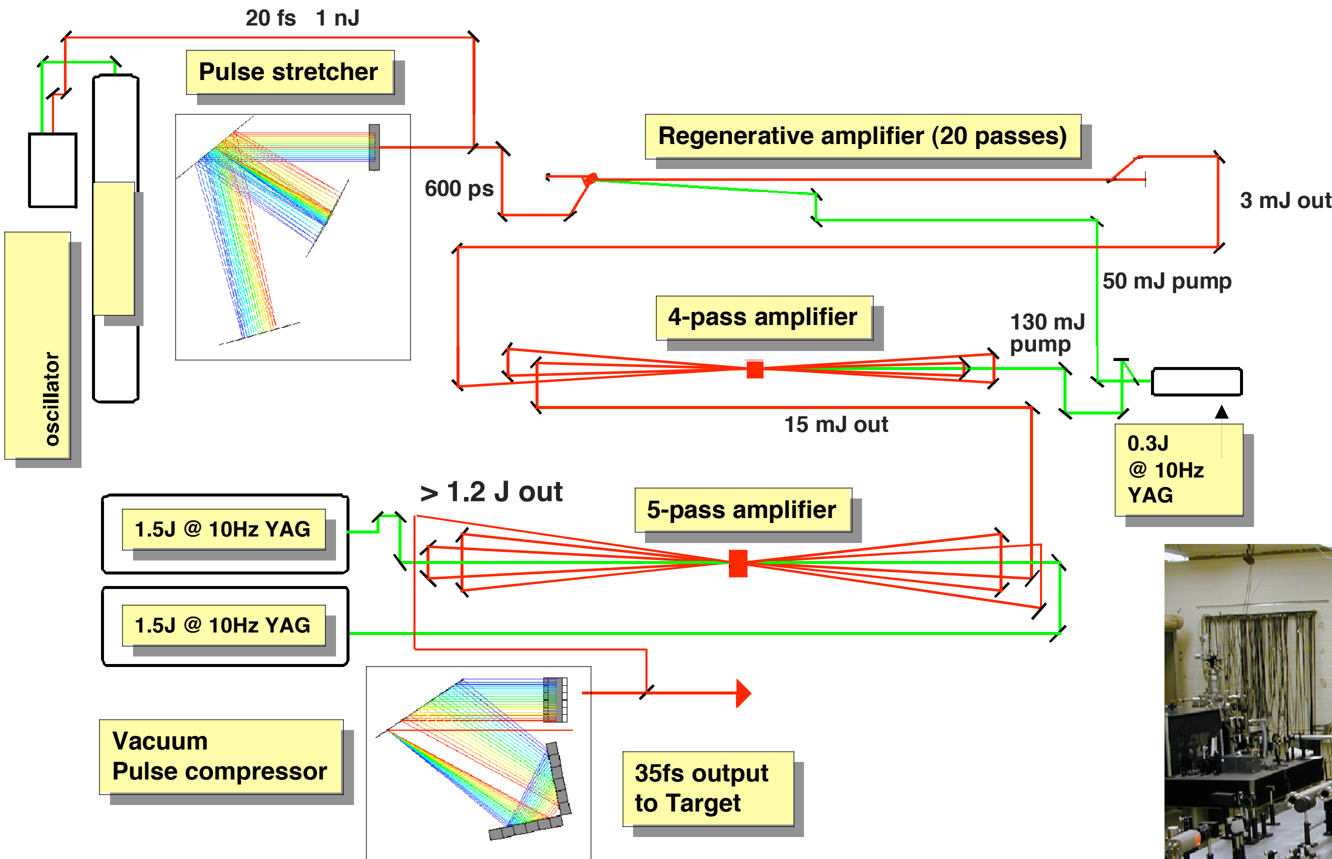
Pulse energy 10 - 1000 J
Pulse duration > 500 fs
Peak power 10 - 1000 TW
Repetition rate ~ 1 shot/hour

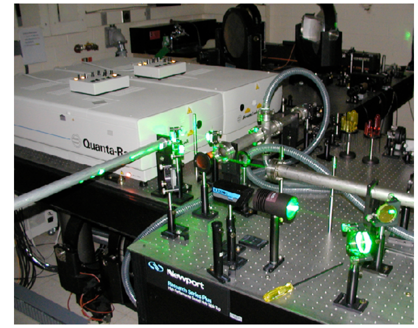
Usually Nd:glass based

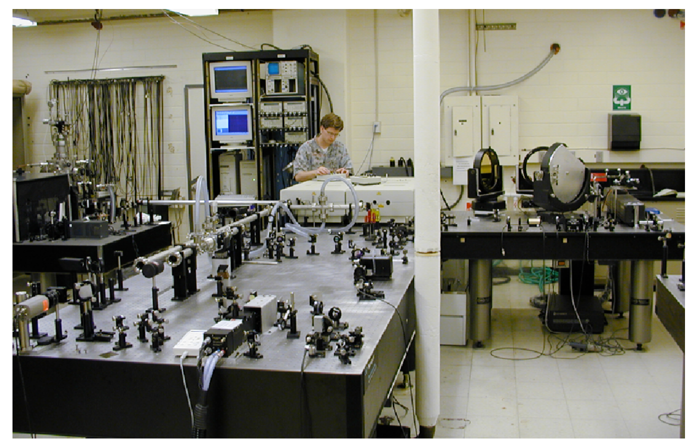




The "Texas High intensity Optical Research laser" (THOR) is a table top 20 TW laser

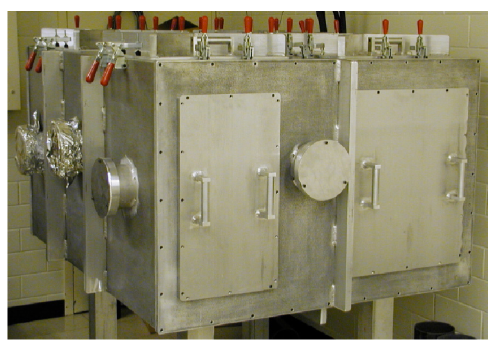






Present performance specs:

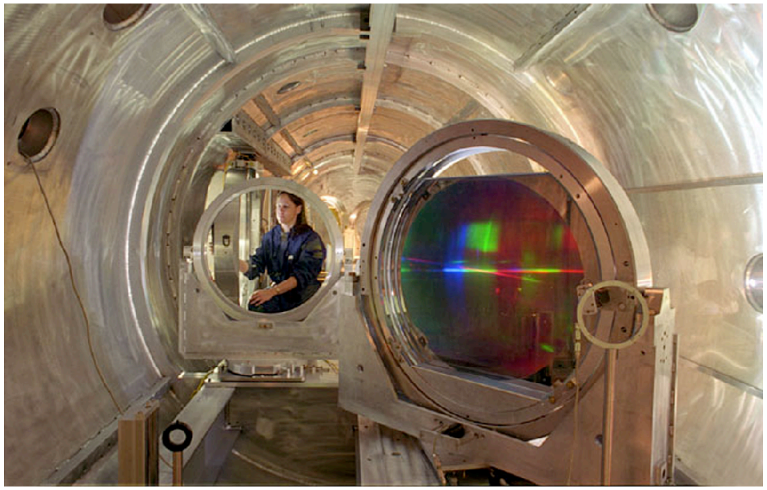
~ 35 fs pulsewidth
0.75 J energy @ 10 Hz
 ~ 20 TW peak power



In 1996, the world's first Petawatt laser was demonstrated at Lawrence Livermore National Lab

The Petawatt at LLNL

Nova laser



90 cm gratings to compress Nova pulses

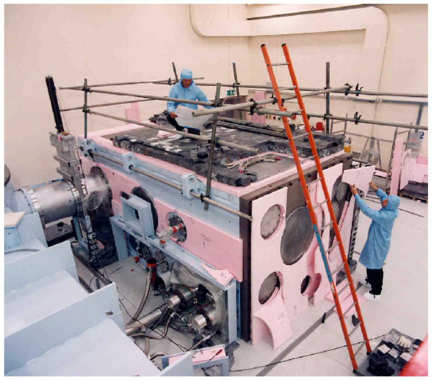
Petawatt specs:
500 J energy
500 fs pulse duration
Peak intensity > 10^{20} W/cm^2

The LLNL Petawatt laser achieved world record focused light intensity of 5×10^{20} W/cm^2

High intensity laser development is very active world wide

List of short pulse laser facilities above 10 TW currently operating world wide

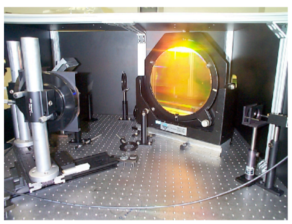
Facility	Peak Power	Type	Pulse duration	Pulse Energy
RAL, UK	1 PW	Nd:glass/OPCPA	600 fs	600 J
ILE, Japan	700 TW	Nd:glass/OPCPA	700 fs	350 J
JAERI, Japan	100 TW	Ti:sapphire	20 fs	2 J
MBI, Germany	100 TW	Ti:sapphire	50 fs	5 J
LLNL, USA	100 TW	Ti:sapphire	100 fs	10 J
LULI, France	100 TW	Nd:glass	300 fs	30 J
LOA, France	100 TW	Ti:sapphire	25 fs	2.5 J
ILE, Japan	60 TW	Nd:glass	500 fs	30 J
LLE, Rochester	30 TW	Nd:glass	1 ns	30 kJ
Lund, Sweden	25 TW	Ti:sapphire	35 fs	1.2 J
CUOS, USA	25 TW	Ti:sapphire	30 fs	1 J
Texas, USA	20 TW	Ti:sapphire	35 fs	0.7 J
Jena, Germany	17 TW	Ti:sapphire	60 fs	1 J
Ibaraki, Japan	13 TW	Ti:sapphire	50 fs	0.6 J
CREOL, USA	13 TW	Cr:LiSAF	75 fs	1 J
CUOS, USA	10 TW	Nd:glass	400 fs	4 J
NRL, USA	10 TW	Nd:glass	500 fs	5 J
ILE, Japan	10 TW	Ti:sapphire	100 fs	1 J
LBNL, USA	10 TW	Ti:sapphire	45 fs	0.5 J
RAL, UK	10 TW	Ti:sapphire	50 fs	0.5 J
Soreq, Israel	10 TW	Ti:sapphire	45 fs	0.45 J
Garching, Germ.	10 TW	Ti:sapphire	100 fs	1 J

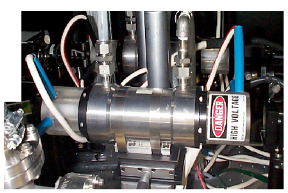


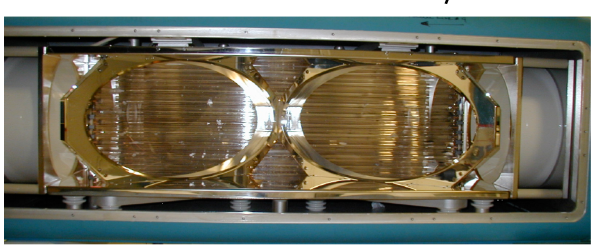
PW lasers under construction:

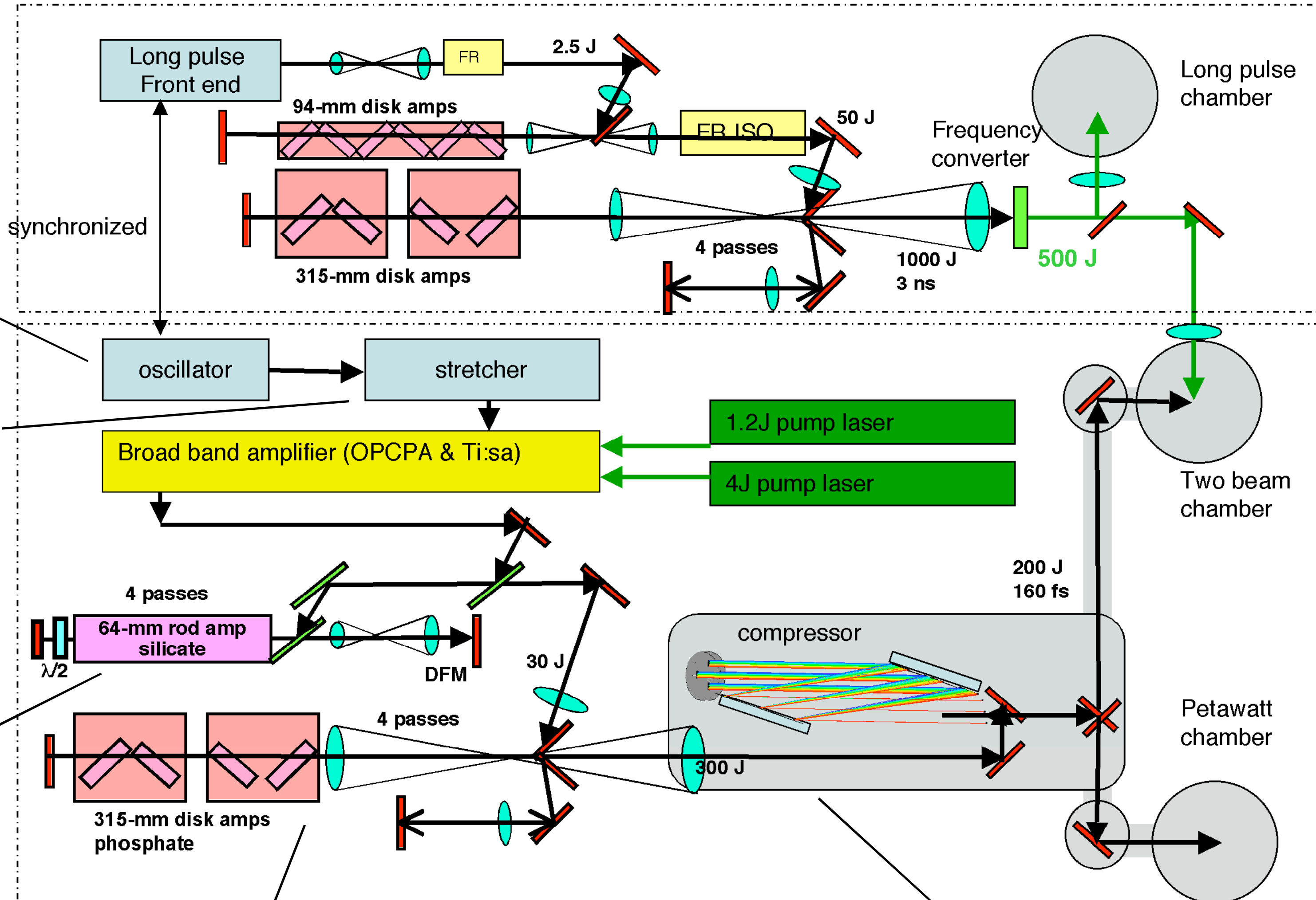
JAERI, Japan
LULI, France
Sandia, USA
U. Texas, USA
CELIA+CESTA, France
Jena, Germany
GSI, Germany
UT, Texas

We have initiated the construction of the Texas Petawatt laser

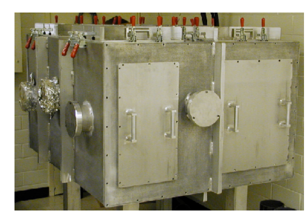








Large amps from Nova beam lines



Chirped pulse amplification lasers access extreme regimes of physical parameter space

Multi-TW laser focused to <10 μm

↓

Focused light intensity of

> 10^{18} - 10^{20} W/cm^2

High Field Science

High electric fields

$E \sim 10^{10}$ - 10^{11} V/cm

Field strength is 10 to 100 times that of the electric field felt by an electron in a hydrogen atom

High electron quiver energy

U_{osc} = 60 *keV* - 3 *MeV*

Electron motion can become relativistic ($U_{osc} > m_e c^2$ = 512 *keV*)

High Energy Density Science

Concentrated energy

Energy density in a femtosecond pulse is 10^9 J/cm^3

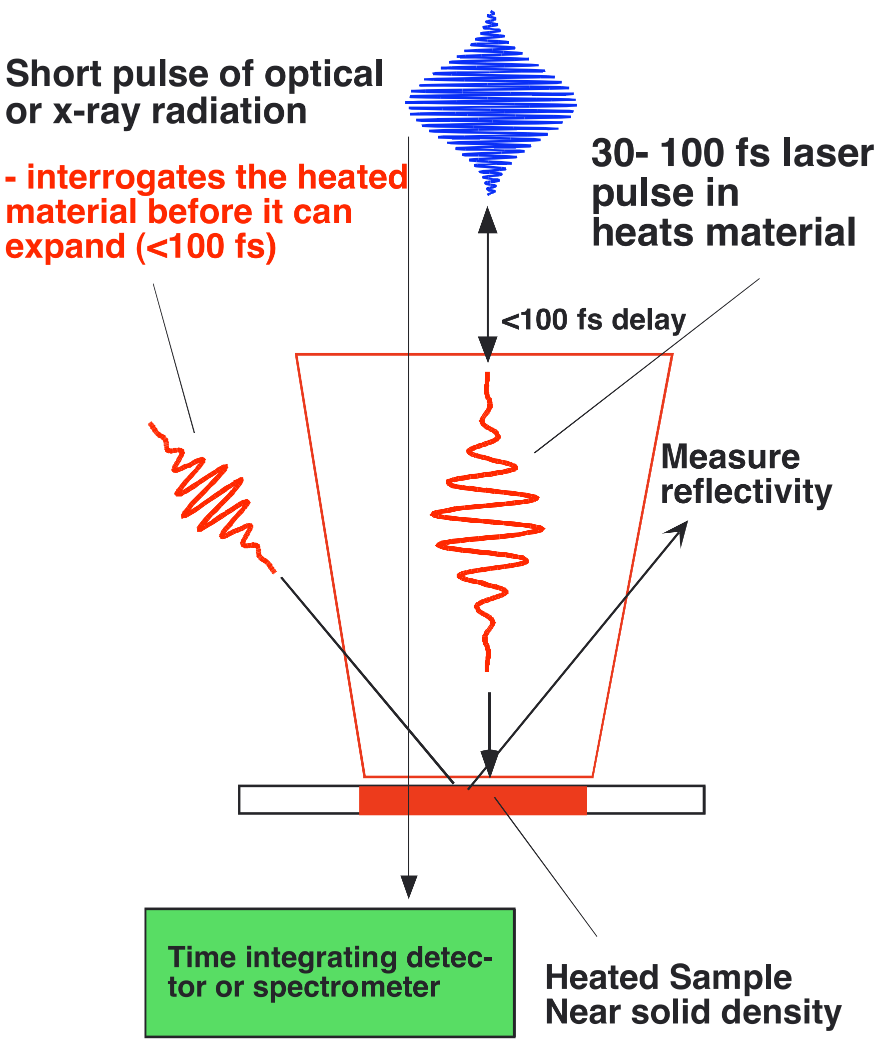
Corresponds to ~ 10 keV per atom at solid density

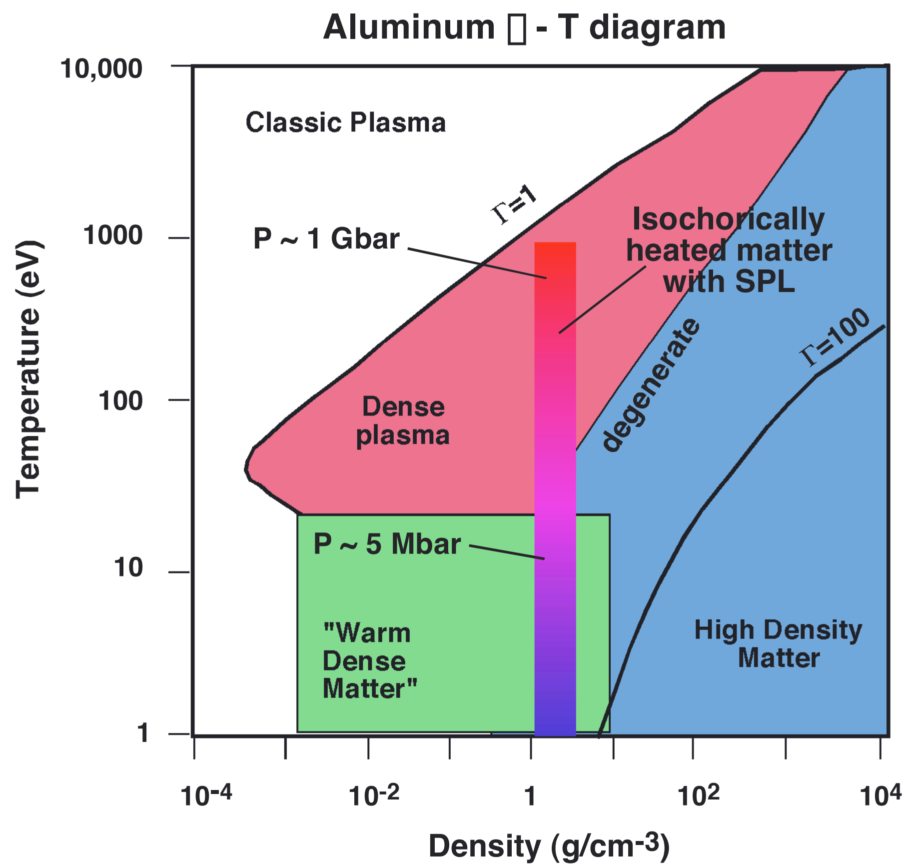
High brightness and pressure

Radiance exceeds that of a 10 keV black body

Light pressure $P = I/c$ = 0.3 - 30 *Gbar*

A short pulse laser can isochorically heat materials to high temperature and pressure



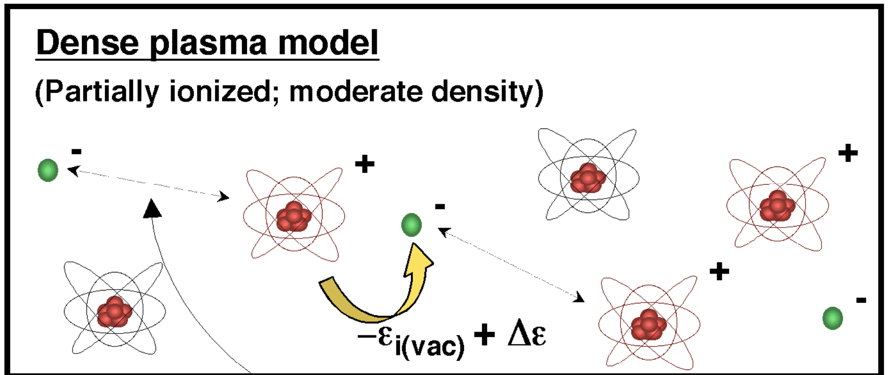


Target expands ~ d/c_s

~ 10 nm/ 5 x 10^6 cm/s (for 100 eV Al)

~ 200 fs

The high density plasmas created by laser isochoric heating exhibit dramatic alteration of atomic structure by plasma fields



Energy gained from interaction with plasma

Screening in plasmas reduces the potential associated with each ion

$$V_{ion}^{(plas)}(r) = V_{ion}^{(0)}(r) \cdot \exp\left(-\frac{r}{\rho_D}\right)$$

Saha: (Partially ionized, dense plasma)

$$\frac{N_e N^{(z)}}{N^{(z-1)}} = \frac{2Z^{(z)}(T)}{Z^{(z-1)}(T)} \left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_\infty^{(z-1)} - \Delta E_\infty^{(z-1)}}{kT}\right)$$

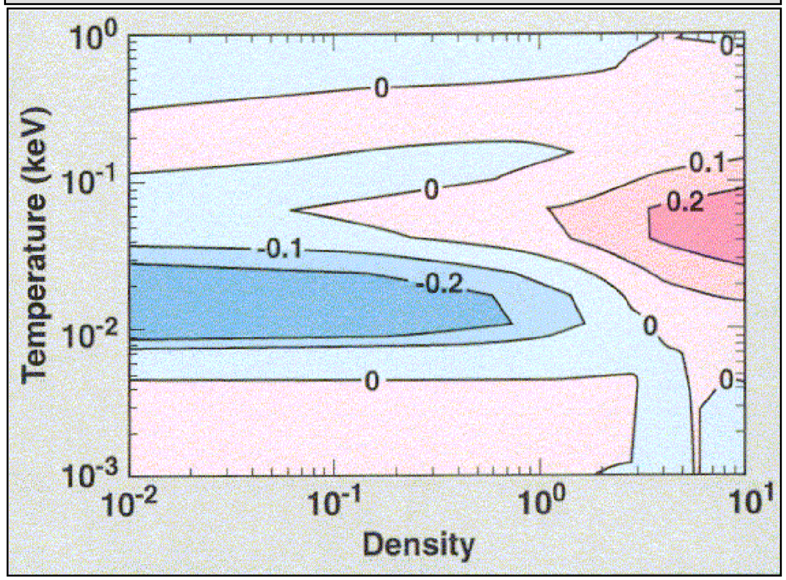
Example -- Aluminum: First ionization energy = 5.89eV

Density -> kT	10^{-6} * S.D.	10^{-2} * S.D.	10^{-1} * S.D.	0.4 * S.D.
5eV	ΔE ≈ .05eV	ΔE ≈ 1.6eV	ΔE ≈ 3.8eV	ΔE ≈ 5.8eV (!)
2eV	ΔE ≈ .05eV	ΔE ≈ .95eV	ΔE ≈ 2.1eV	ΔE ≈ 4.2eV

In the warm/hot dense matter regime sizeable errors exist in the equation of state

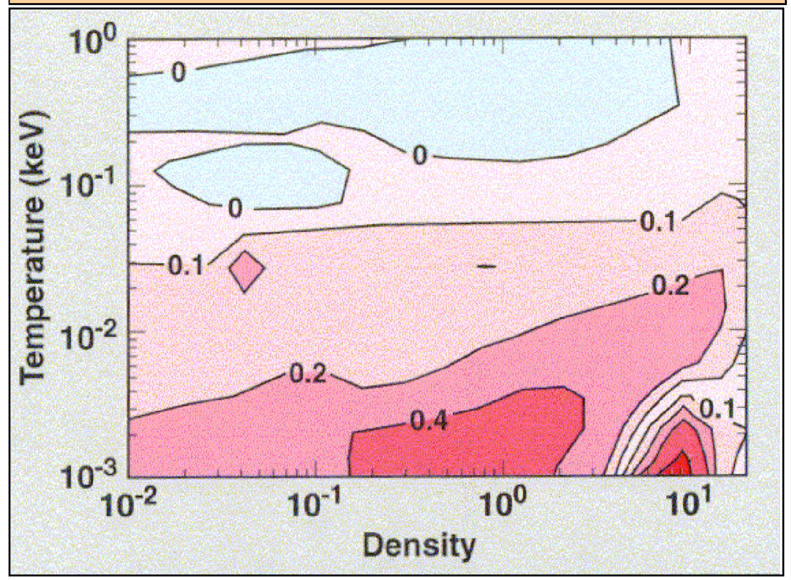
Contours of % difference in pressure

Model uncertainty for Al pressure



- Simple atomic physics
- Although most studied, differences of more than 20% in calculated pressure values can be found in the regime for hot expanded states;

Model uncertainty for Cu pressure



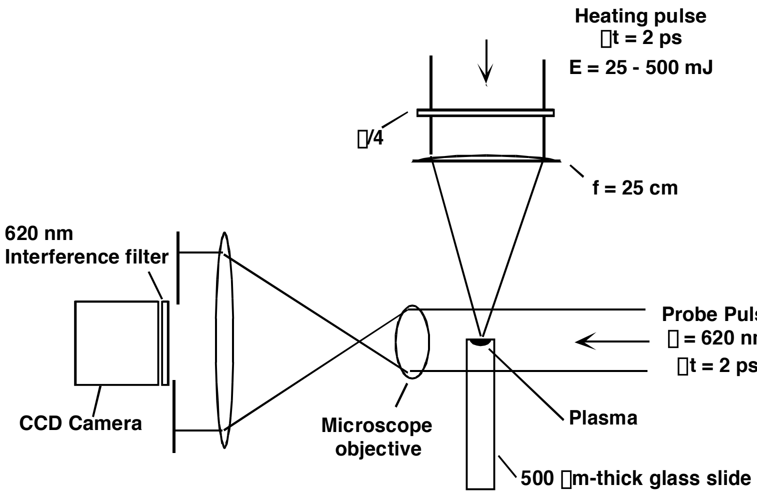
- Complex atomic physics - d-shell electrons
- Large model differences in the WDM region
- Measurements required for guidance

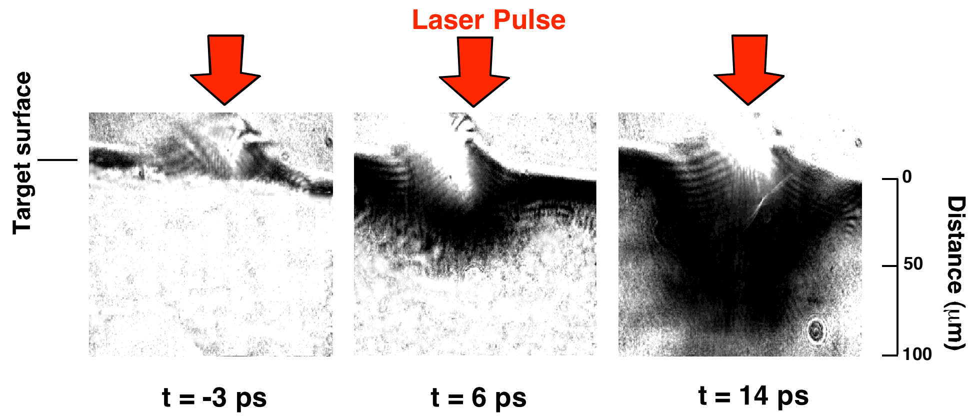
Implementation of atomic physics in this (ρ, T) regime is very challenging

R. W. Lee 2002

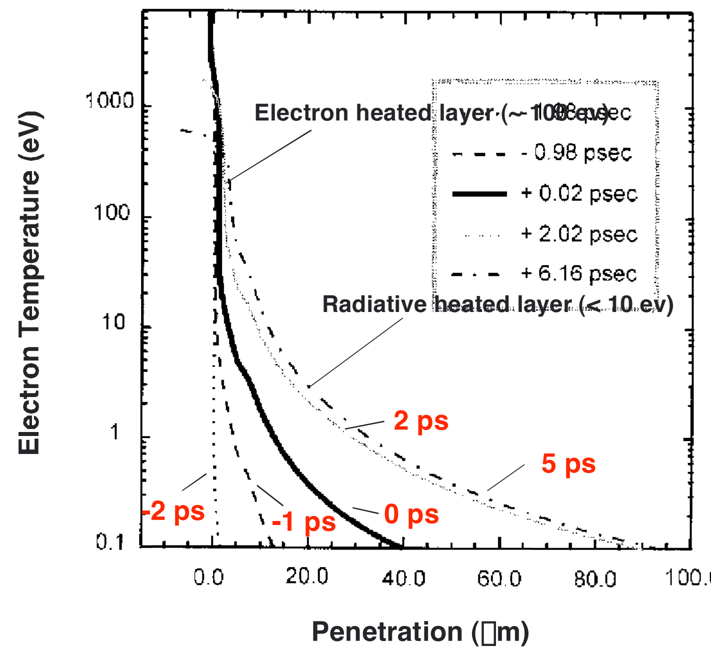
Ultrafast electron and radiative heat conduction distribute laser energy in the underlying material

Picosecond optical probing of heat transport driven ionization wave in fused silica from laser irradiated solid at 2 x 10^{17} W/cm^2





MEDUSA Hydro- simulation of Imperial College experiment on Fused Silica with a 2 ps laser focused to 10^{17} W/cm^2



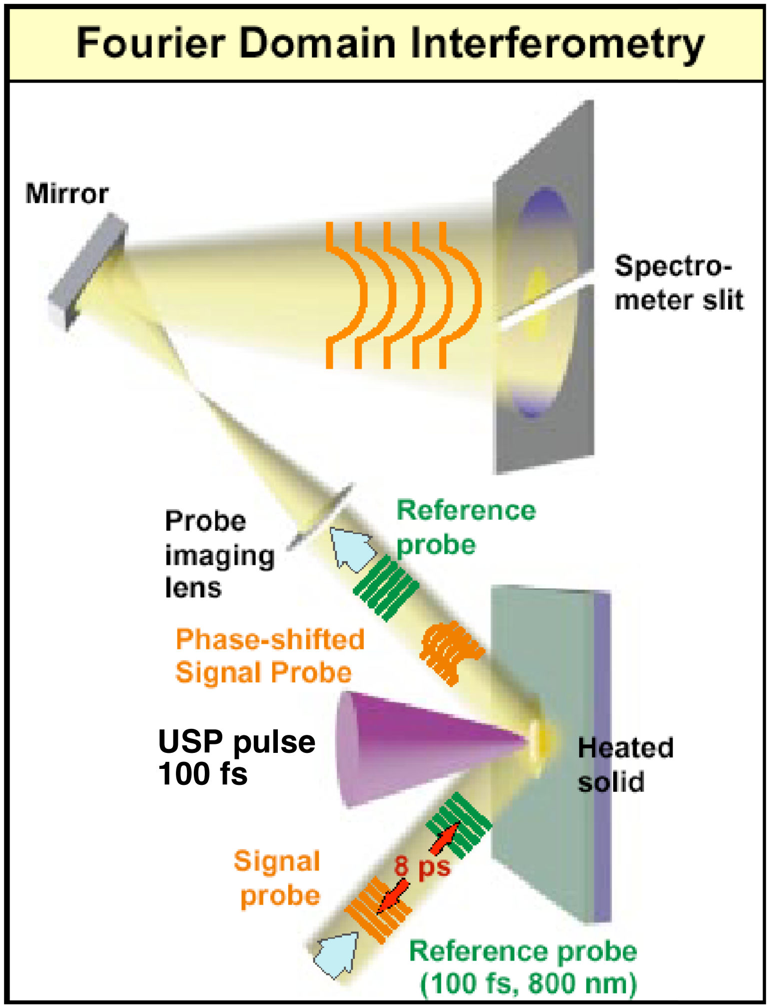
Data and simulation from Imperial College,
***Phys. Rev. Lett*. 77, 498 (1996)**

Using multi-terawatt short pulse lasers in high energy density experiments has important advantages

Unique capabilites in SPL HED experiments:

- Pulse duration much shorter than typical hydrodynamic time
  $\Rightarrow$ excitation and probing of heated material before expansion
- High temperatures potentially attainable
- Off Hugoniot measurements possible
- Capable of generating wide range of probes: optical, XUV, X-rays
- High repetition rate $\Rightarrow$ Systematic studes/ parameter scans

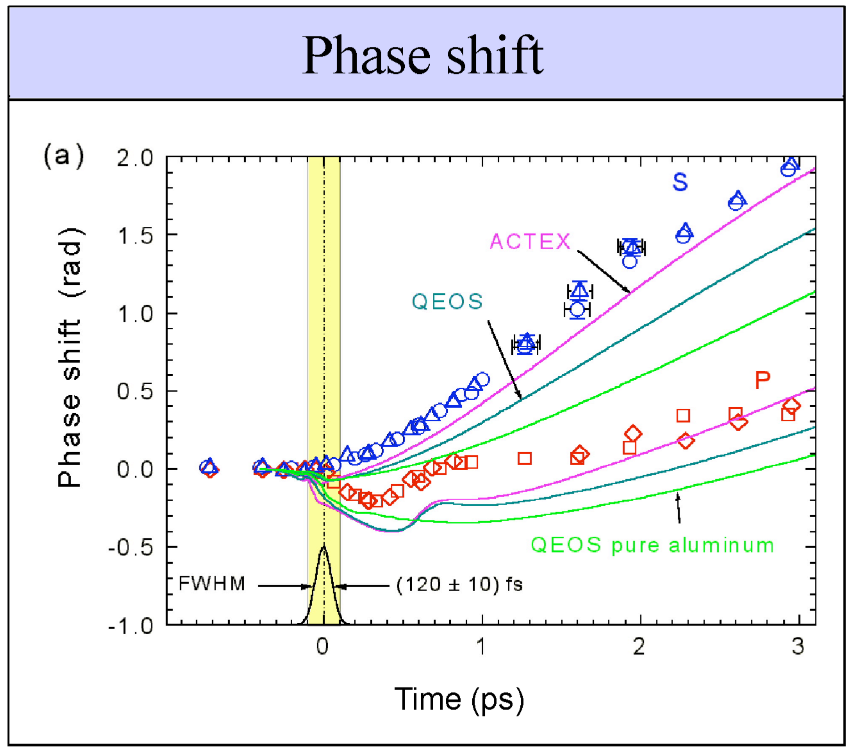
EOS information from isochorically heated matter can be derived by examination of the release velocity of material expanding on an isentrope



Aluminum target: 4300 Å Al, 26 Å Al_2O_3, and 3 Å CH_2.

Heating-pulse intensity at target surface: $I = 1.0(8)\cdot10^{14}$ W/cm^2

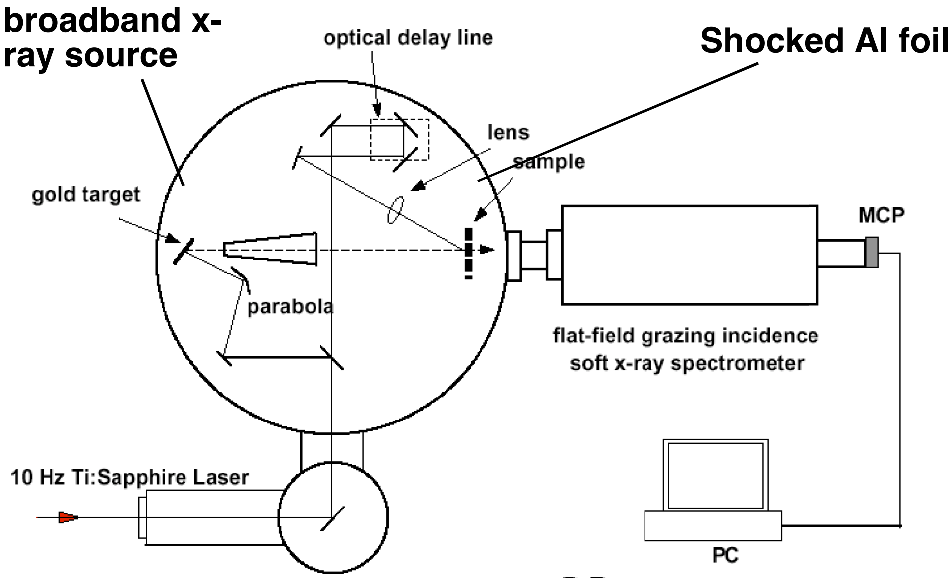
Areal energy density of heating-pulse : $E_{areal} = 13.0(3)$ J/cm^2

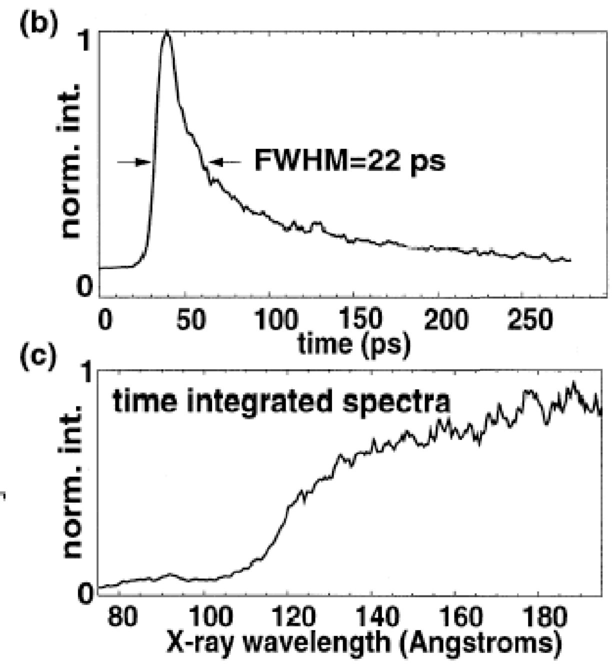


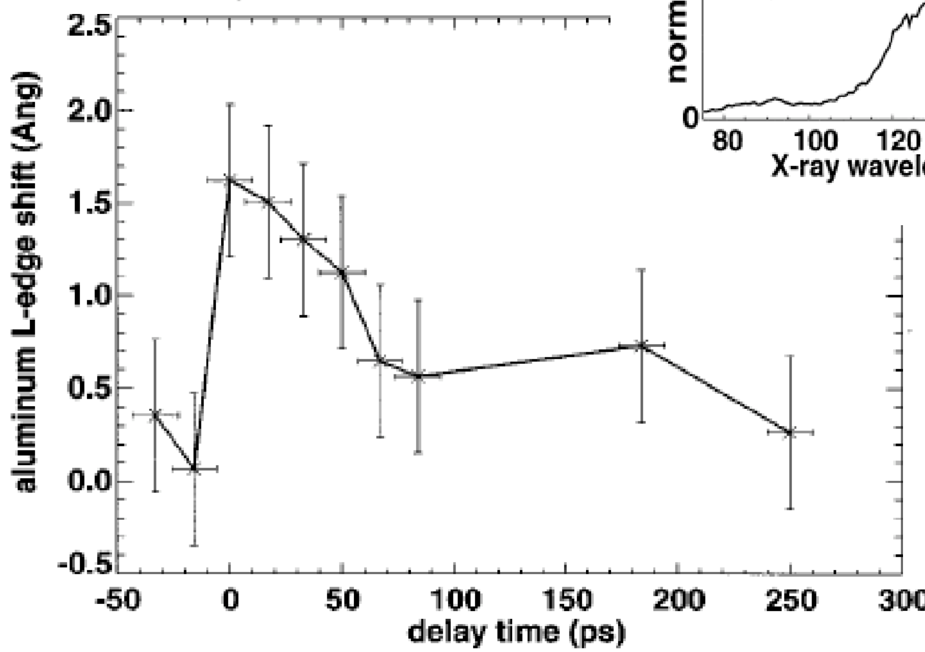
Data from K. Widmann and P. Springer, LLNL

Information on atomic environment in short pulse excited matter can be derived by ultrafast x-ray absorption spectroscopy

University of Michigan results from short pulse shock compressed aluminum:







Data taken from **J. Workman, M. Nantel, A Maksimchuk, and D. Umstadter, *App. Phys. Lett.* 70, 312 (1997).**

Don Umstadter 2001

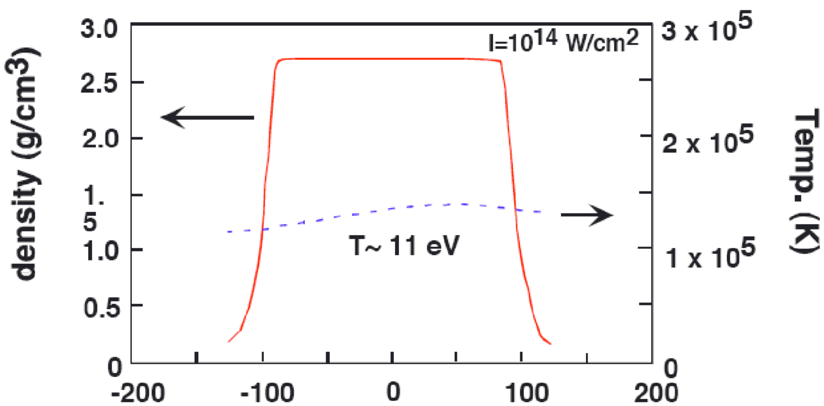
Using ultrafast probing, it may be possible to derive EOS information at solid density and elevated temperature

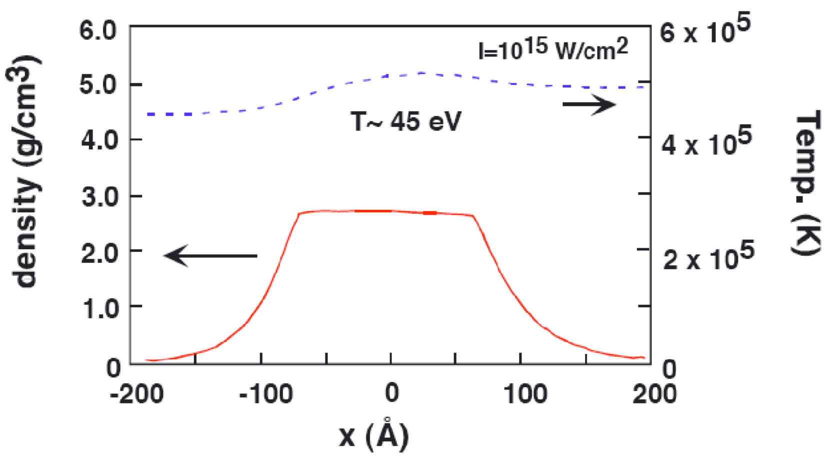
Calculations by A. Ng and coworkers indicate that uniform temperatures can be created in 200-300 Å foils with temperature up t~ 10 eV

$T_e \sim T_i \sim$ 10-40 eV

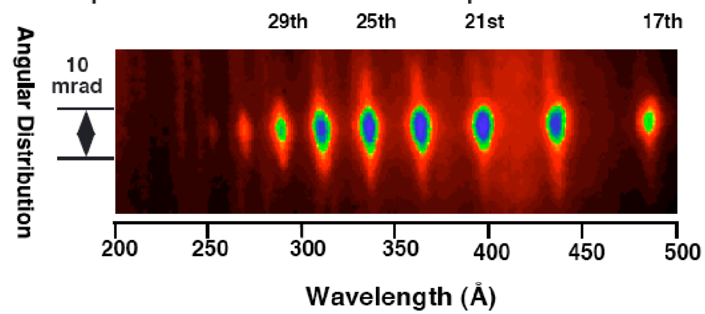
P ~ 5 - 10 Mbar

Al temp. and den. profile after 35 fs pulse heating

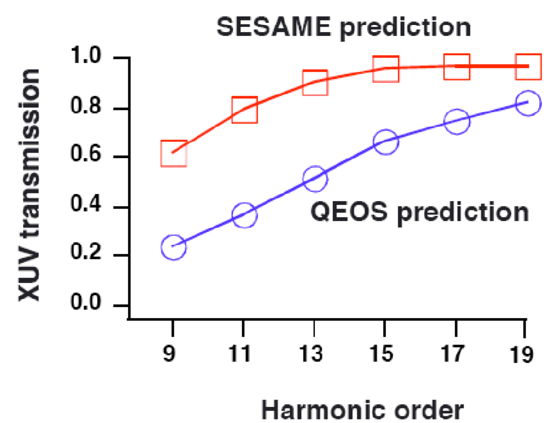




Spatial distribution of harmonics produced a 100 fs laser



Different EOSs lead to quite different XUV opacity predictions



Problems remain to be solved if truly quantitative information is to be derived in short pulse laser heating experiments

Principal issue with multi-TW experiments done to date:

Small heated volumes (<1000 μm^3)/layer thickness (<100 nm) have led to temperature/density gradients, and fast release (too fast for proper equilibration)

Solution:

1) Will require larger heating volumes with larger spot sizes
ie up to 1 mm^2 spot size at >10^{17} W/cm^2

Will require a petawatt class laser

2) Will need to heat thicker layers

10 μm thick layer will release in > 1ps

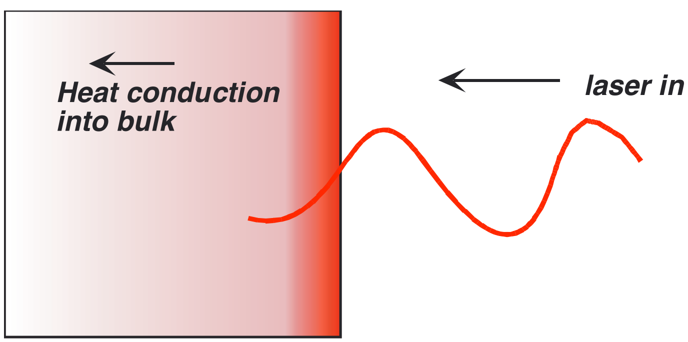
need alternative heating methods (other than optical heating in skin depth)

- hot electrons (as with the fast ignitor)
- fast proton heating
- ultrafast X-rays

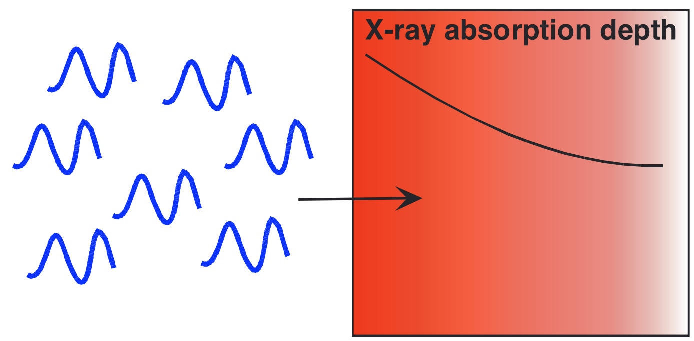
Interesting approach (but low conversion will need high energy, SPL laser (ie Petawatt laser)

Short pulse laser produced x-rays can be used to heat bulk matter isochorically

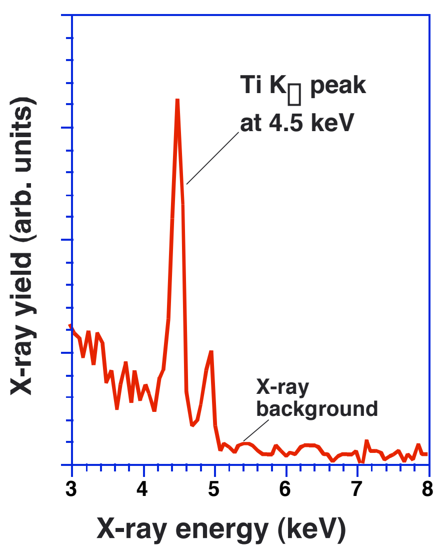
Optical radiation heats only over one skin depth ~10-100 nm

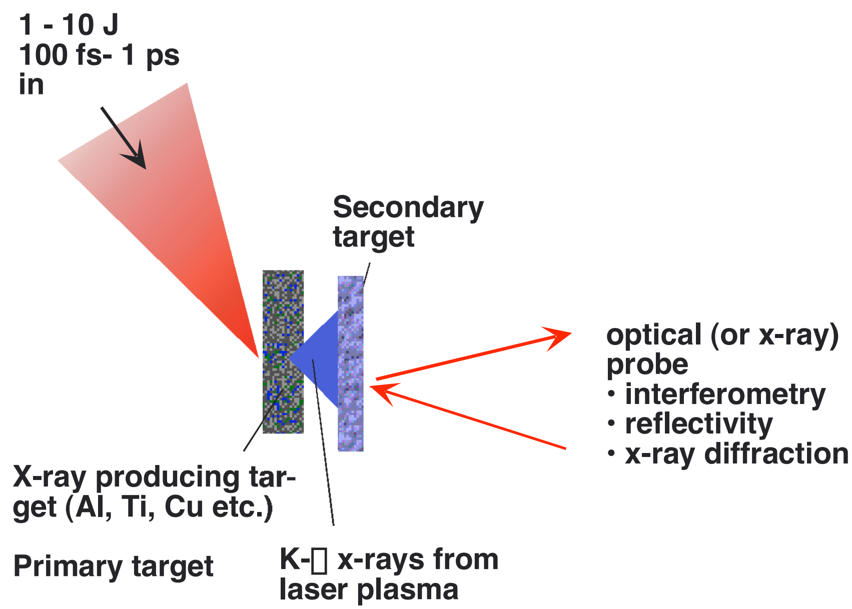


X-rays (1 - 10 keV) deposit energy within the bulk of a target (10-100 mm)



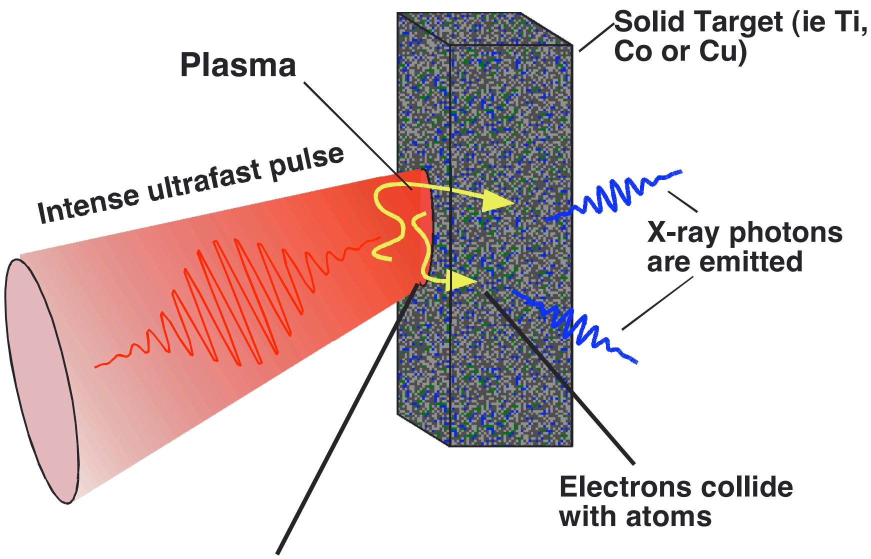
Kα rad from a 35 fs laser at 2 x 10^{17} W/cm^2

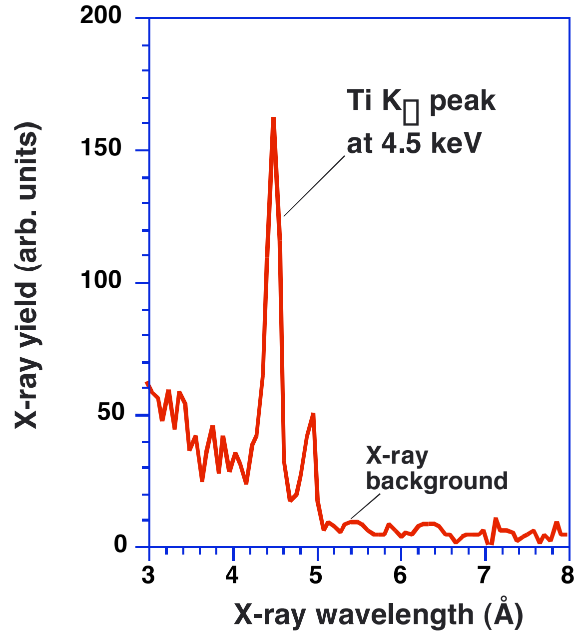




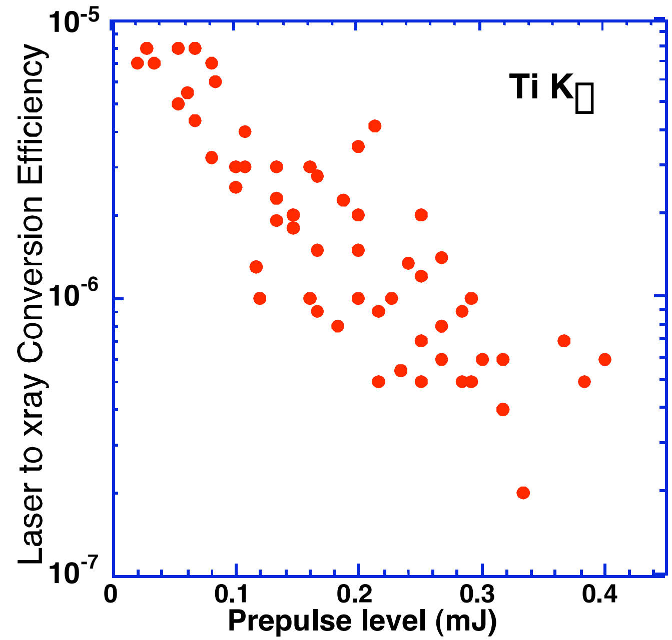
An intense laser focused onto a solid can produce ultrafast x-ray pulses

Intense lasers can also produce x-rays





Strong laser electric field accelerates electrons → T_{hot} ~ 10 - 100 keV

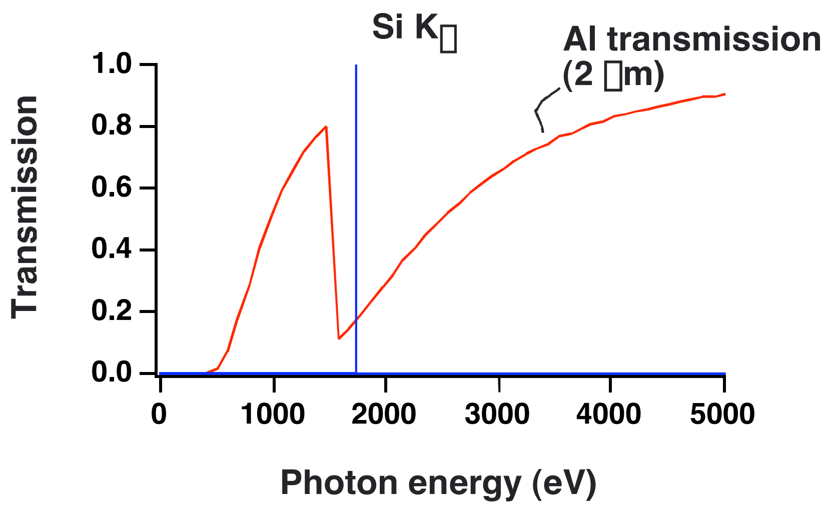


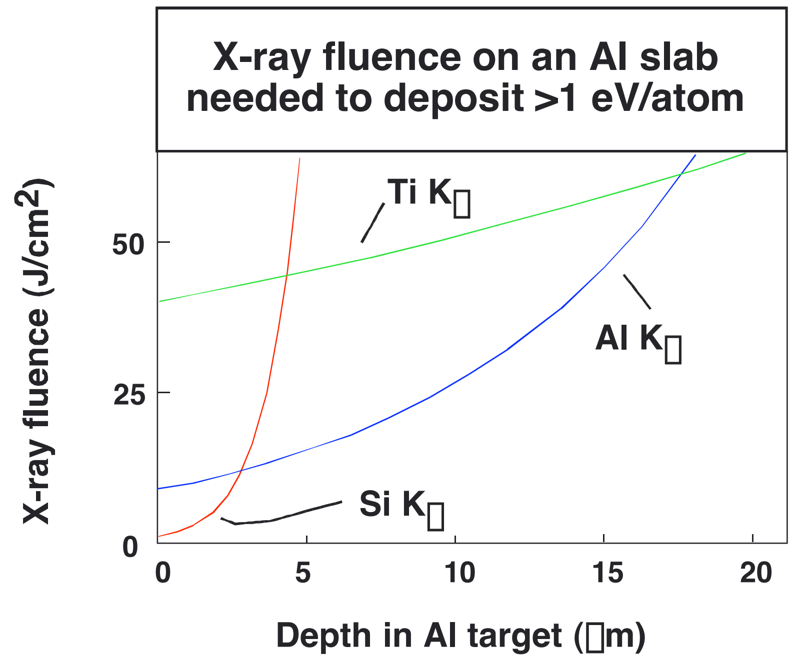
Conversion to x-rays can be ≥10^{-5} of the laser energy

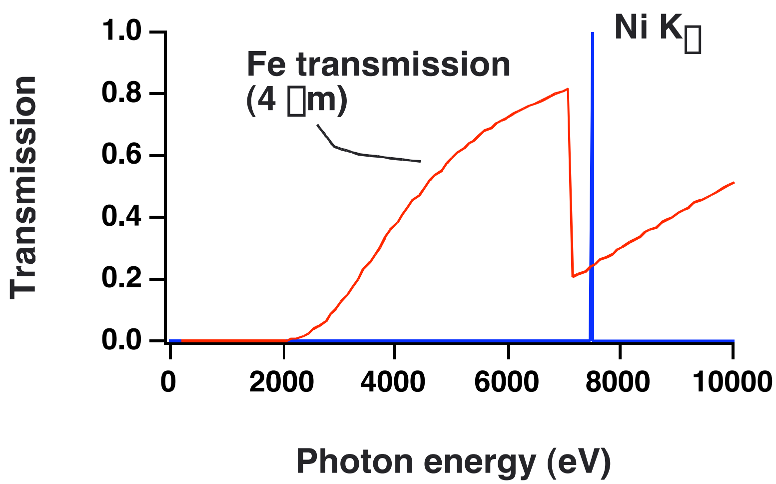
Furthermore, these x-rays are, like the laser pulse, ultrafast

Primary/secondary layer targets can be designed to optimize x-ray deposition rate and depth

Energy deposition can be maximized with judicious choice of x-ray emitter material







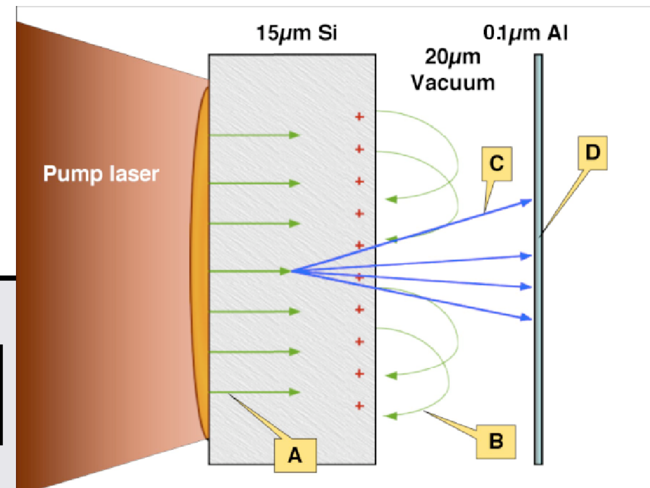
- X-ray fluence for 1 eV/atom in Al = 1.5 J/cm^2
- At 10^{-4} conversion eff.* laser fluence = 15 kJ/cm^2
- A 100 fs laser intensity at fluence = 1.5 x 10^{17} W/cm^2

* For softer x-rays ~ 1- 2 keV: See Gordon, Falcone et al. Opt. Lett. 19, 484 (1994)

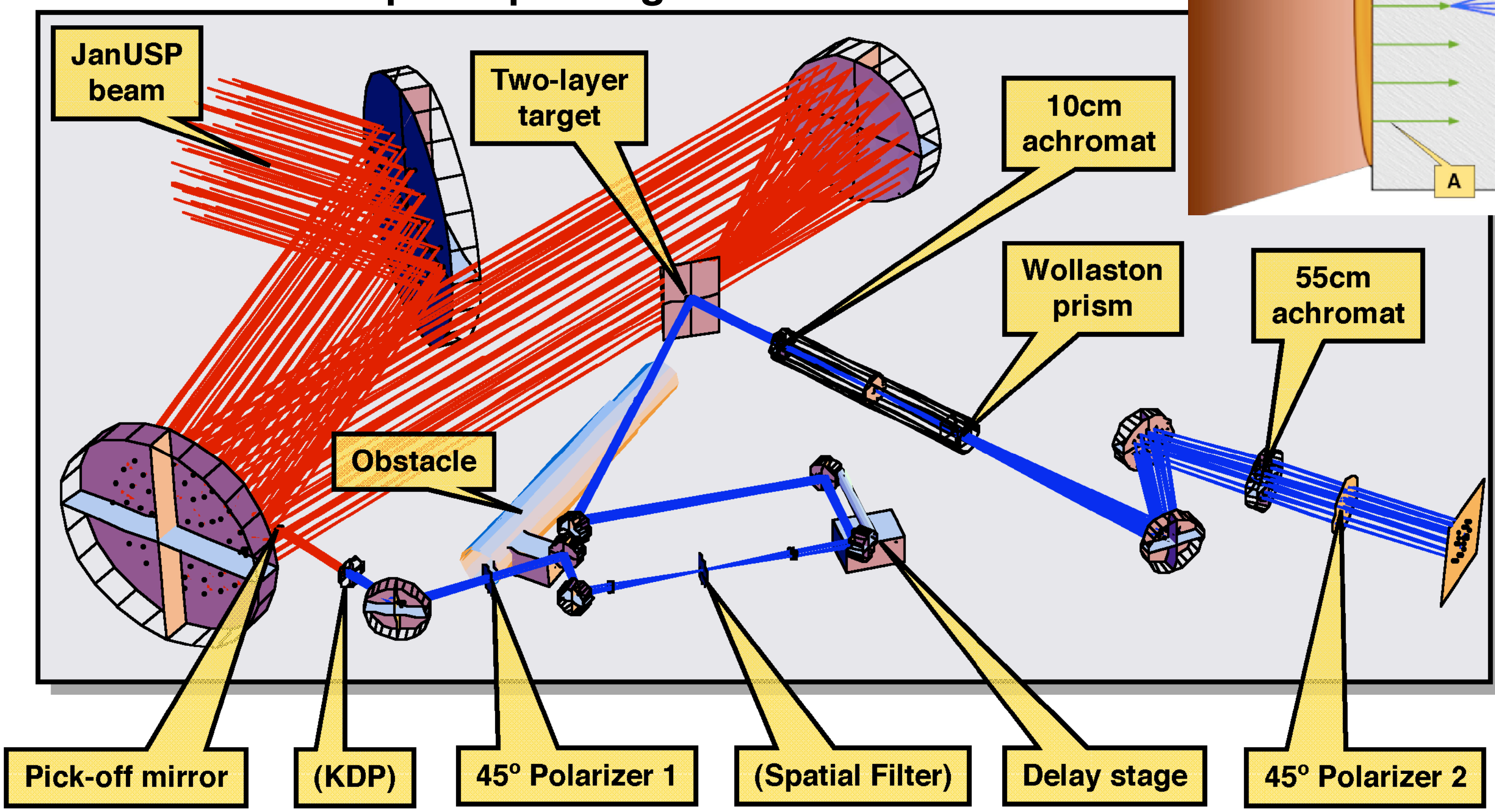
We probe Si K-alpha heating of Al with reflectivity and interferometry

Principal diagnostics include:
Optical probe
X-ray pinhole camera
X-ray CCD as single photon counting spec.
Proton sensitive film

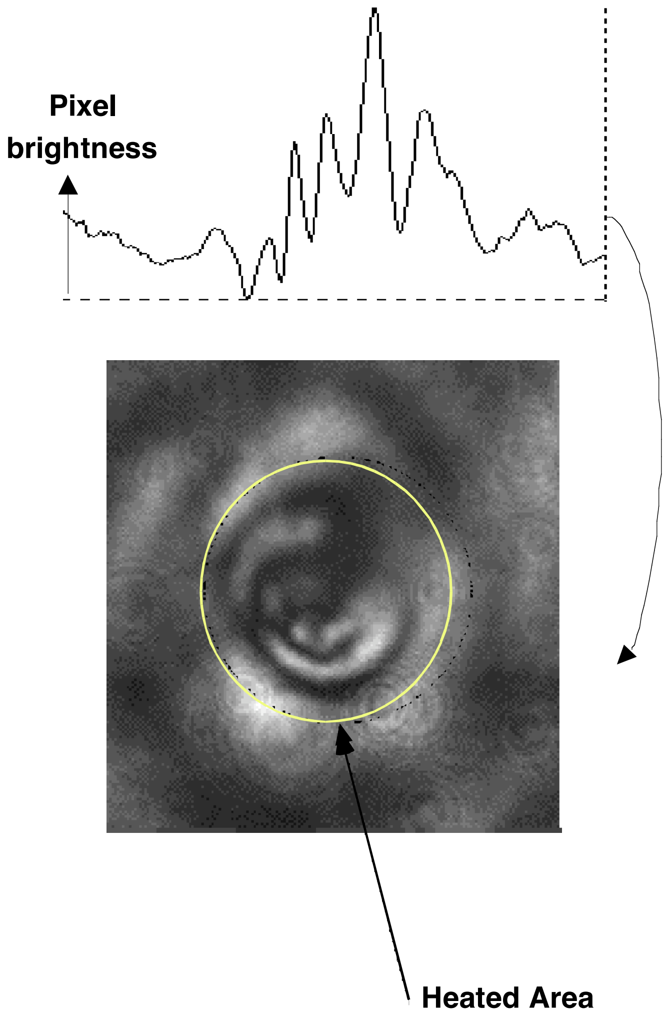
Target Design

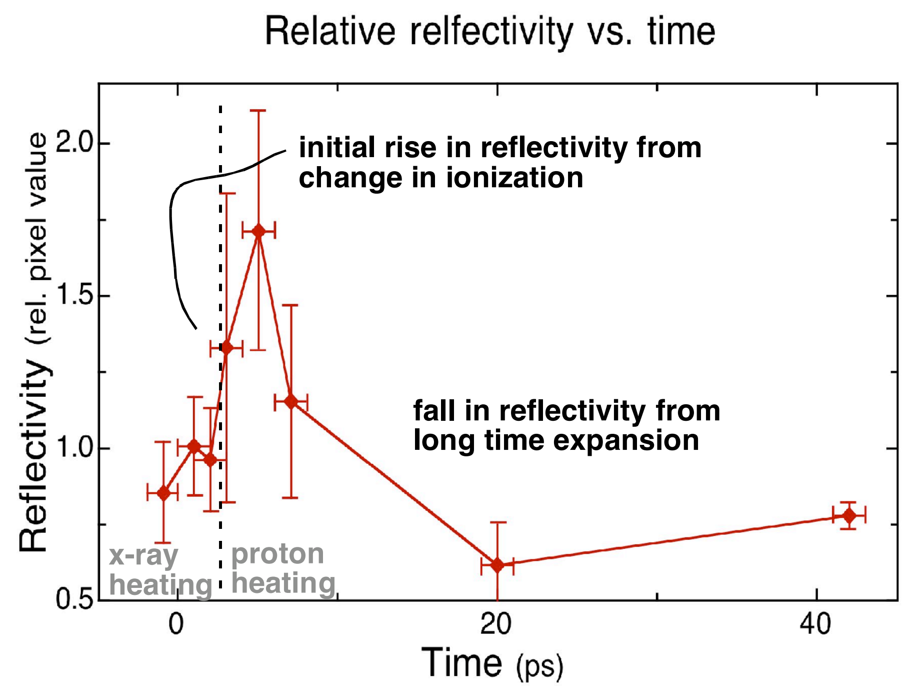


Optical probing schematic



We observe a transient jump in Al reflectivity when heated by x-rays



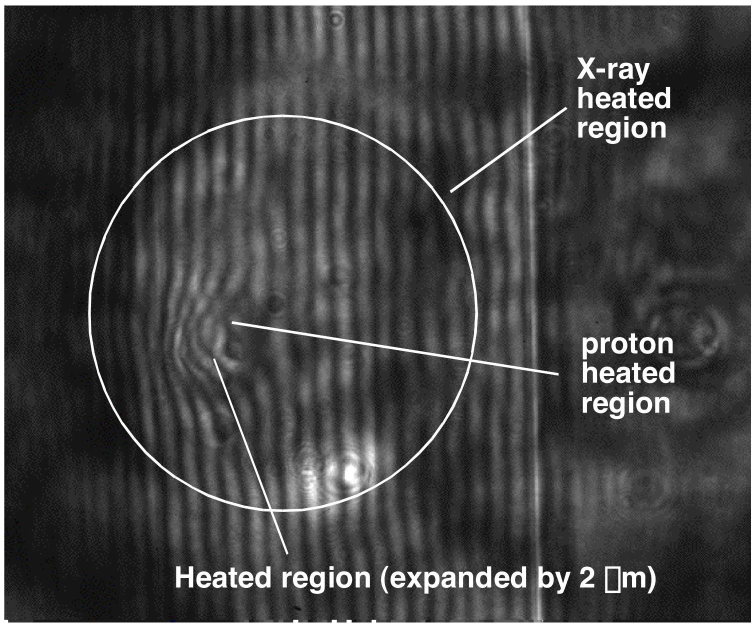


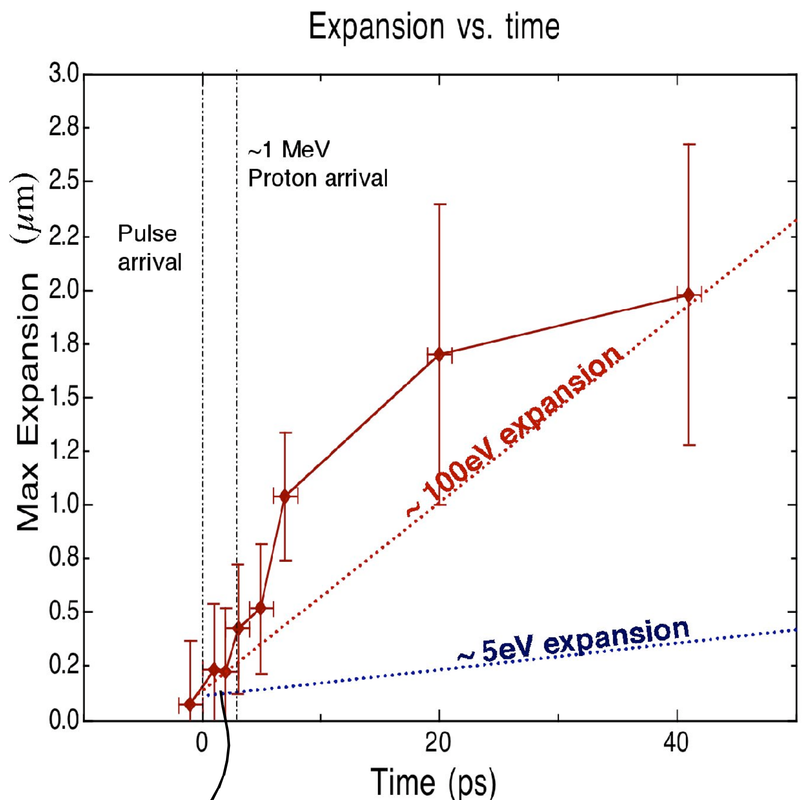
Reflectivity increase may result from Auger electron production of free electron plasma

- **Probe is at 800 nm: reflectivity in cold Al is lowered by an interband transition (to ~75%)**
- **X-ray pulse promotion of free electrons should increase reflectivity**

We have observed expansion and reflectivity changes of X-ray heated Al

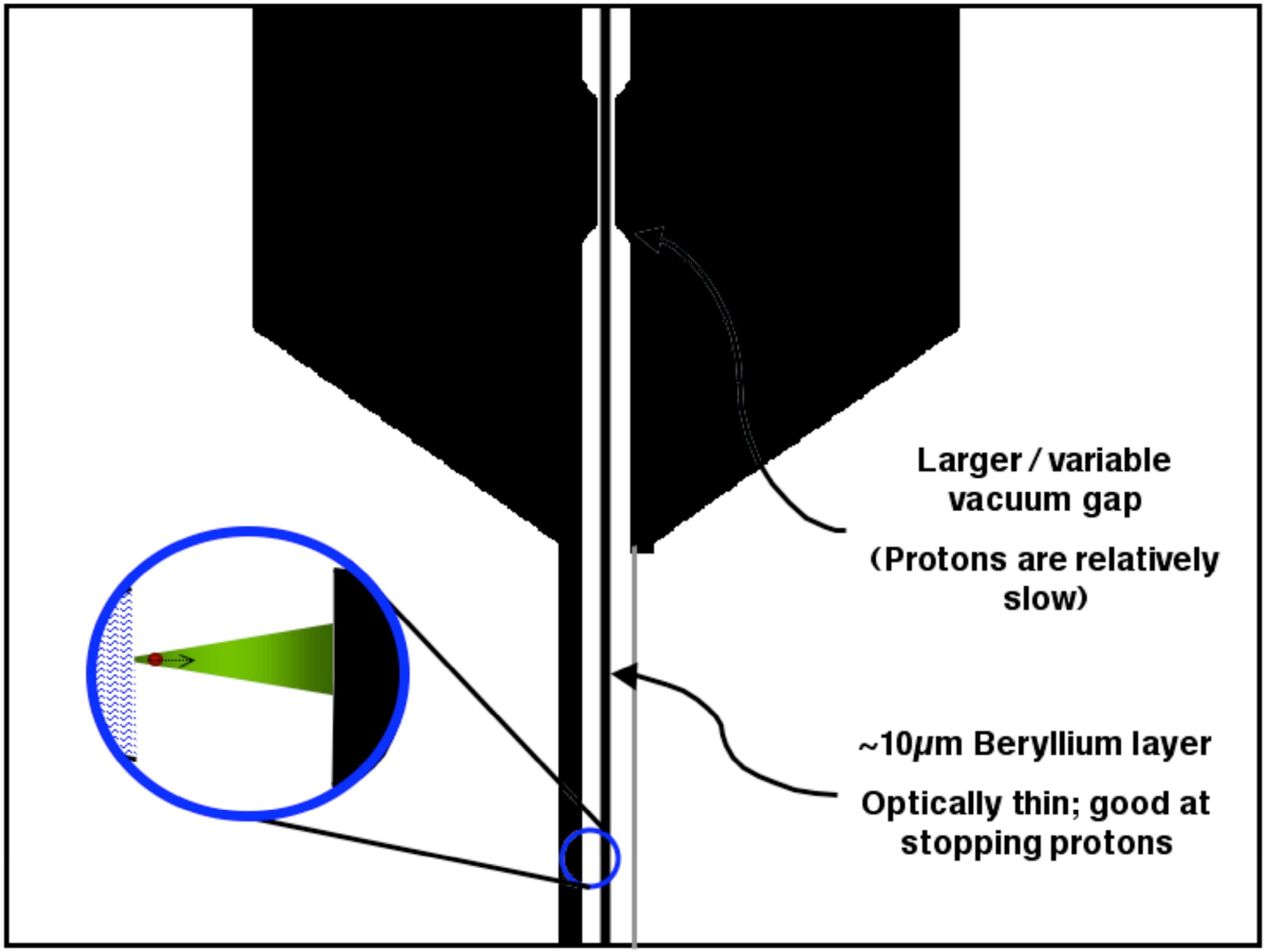
Interferometry image at 40 ps after x-ray irradiation





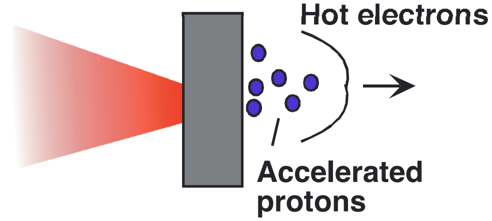
Initial slow expansion is from x-ray pulse arrival

We are working on designs of more sophisticated targets for x-ray heating experiments



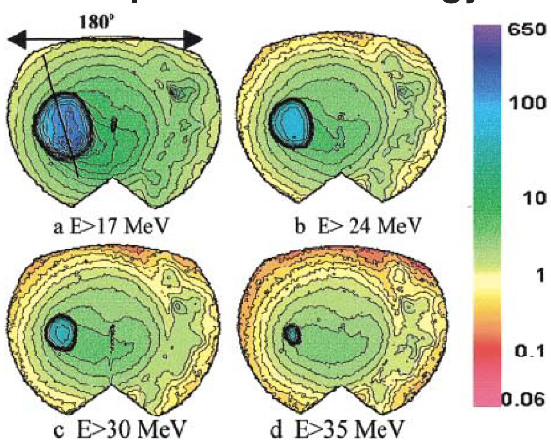
Fast electrons created by the intense laser can drive proton acceleration with an ambipolar potential

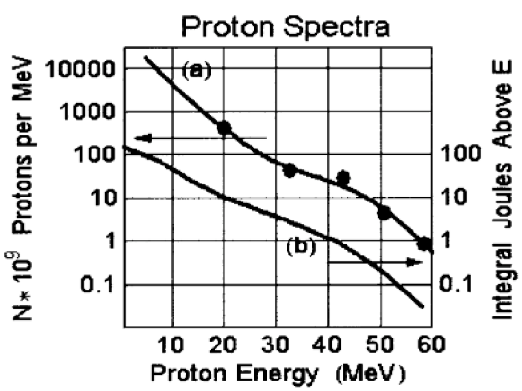
Relativistic electrons produced by a SPL can accelerate protons from a solid



At 3 x 10^{20} W/cm^2 on LLNL PW laser:

Up to 48J of protons (12% of laser energy) were observed in protons with energy >10 MeV





From Snavely et al. PRL 85, 2945 (2000)

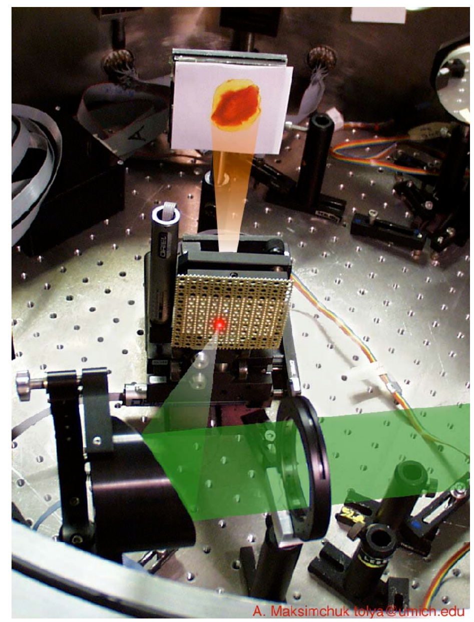
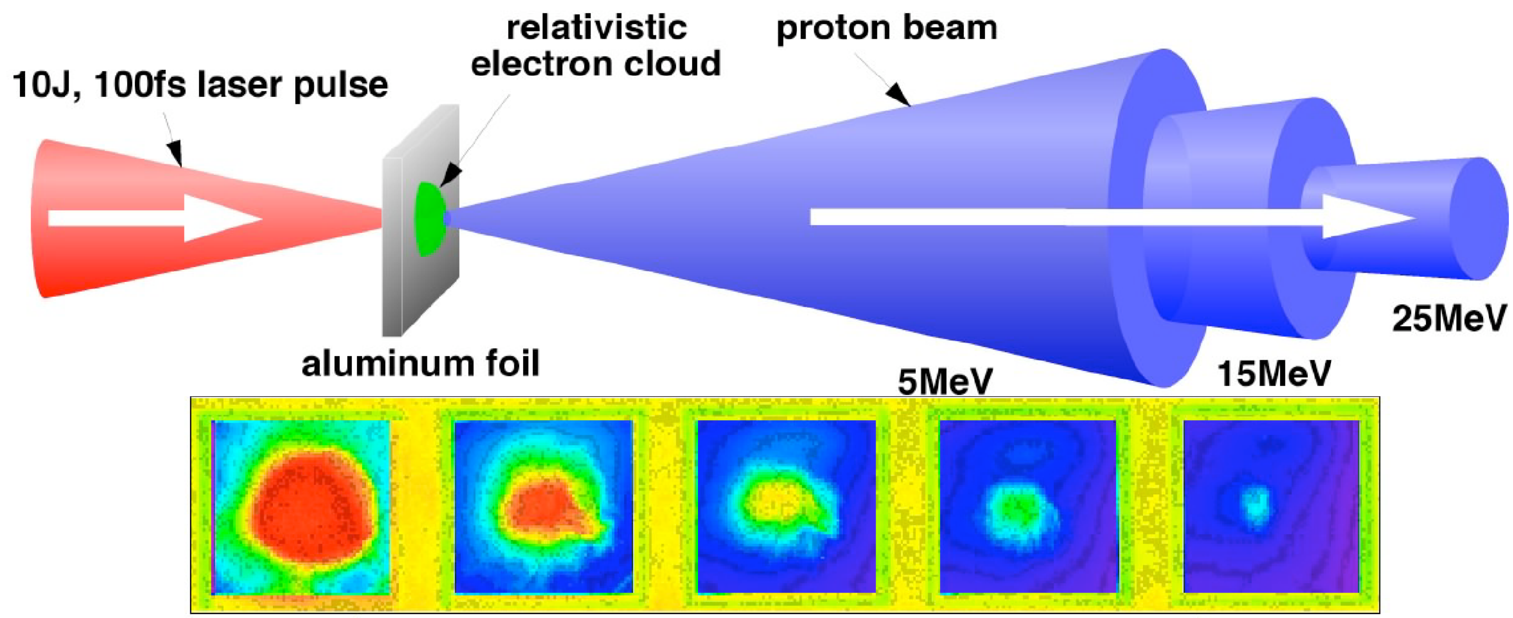


Photo of 1 MeV protons on a phosphor screen on the U. Michigan T^3 laserat intensity > 10^{19} W/cm^2 (from Umstader et al.)

Proton acceleration data from LLNL

Ultra-high intensity laser pulses can efficiently generate intense, energetic beams of protons



Laser-Ion diode Characteristics

- Transverse emittance: < 0.006 π mm-mrad
- Longitudinal emittance: < keV-ns (velocity correlated)
- Energy spread: 100%
- Bunch charge: $10^{11} – 10^{13}$ protons/ions
- Source diameter: ~50 μm (fwhm)
- Charge state purity: >80% He-like
- Particle current: >100 kA (at source)
- Laser-ion efficiency: >> 1% (4-20% observed)

P K Patel *et al*

Example of proton focusing from LLNL

LLNL has recently pioneered the ballistic focusing of proton beams - it is being developed for EOS and FI at NIF

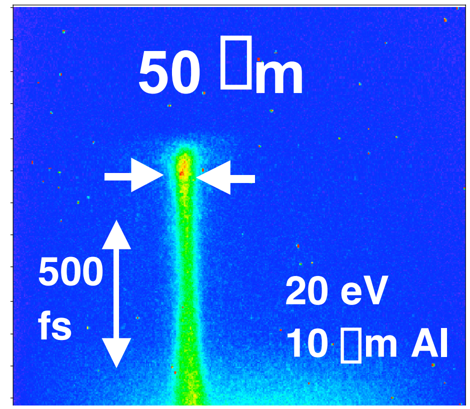
The National Ignition Facility

- Focused beam gives 8x more temp rise than unfocused

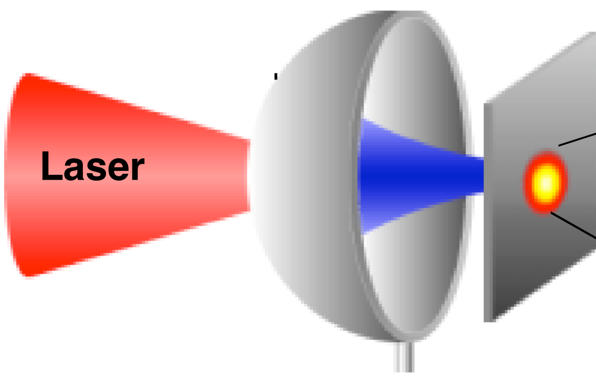
- Focused protons give 2 to 3 x temperature obtained with electron heating

Streak visible image JanUSP

P Patel et al.
In press in
Phys Rev Letts

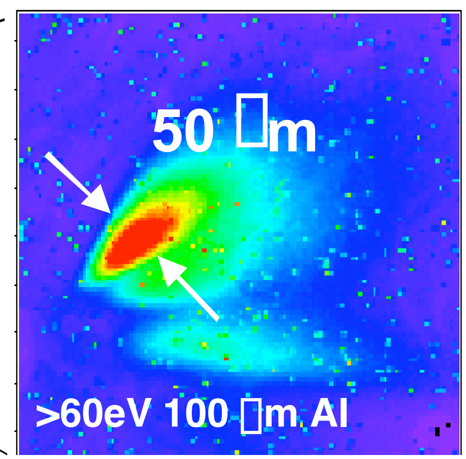


XUV image at Gekko PW in Japan



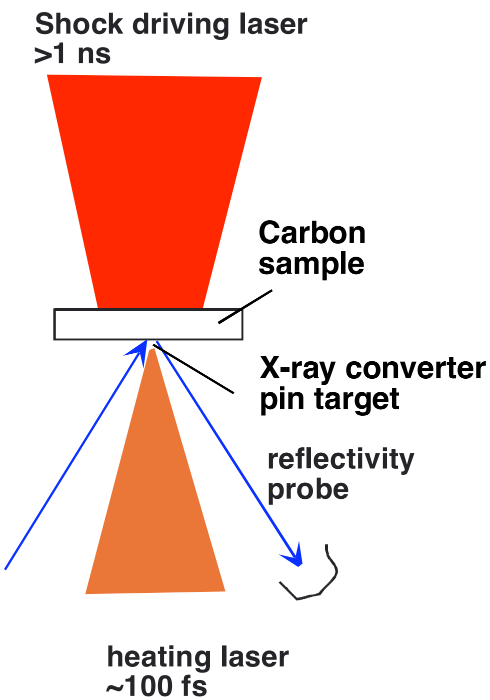
Al hemisphere shell
320 μm diameter

LLNL,UC Davis,
GA, Osaka Univ.
Collaboration

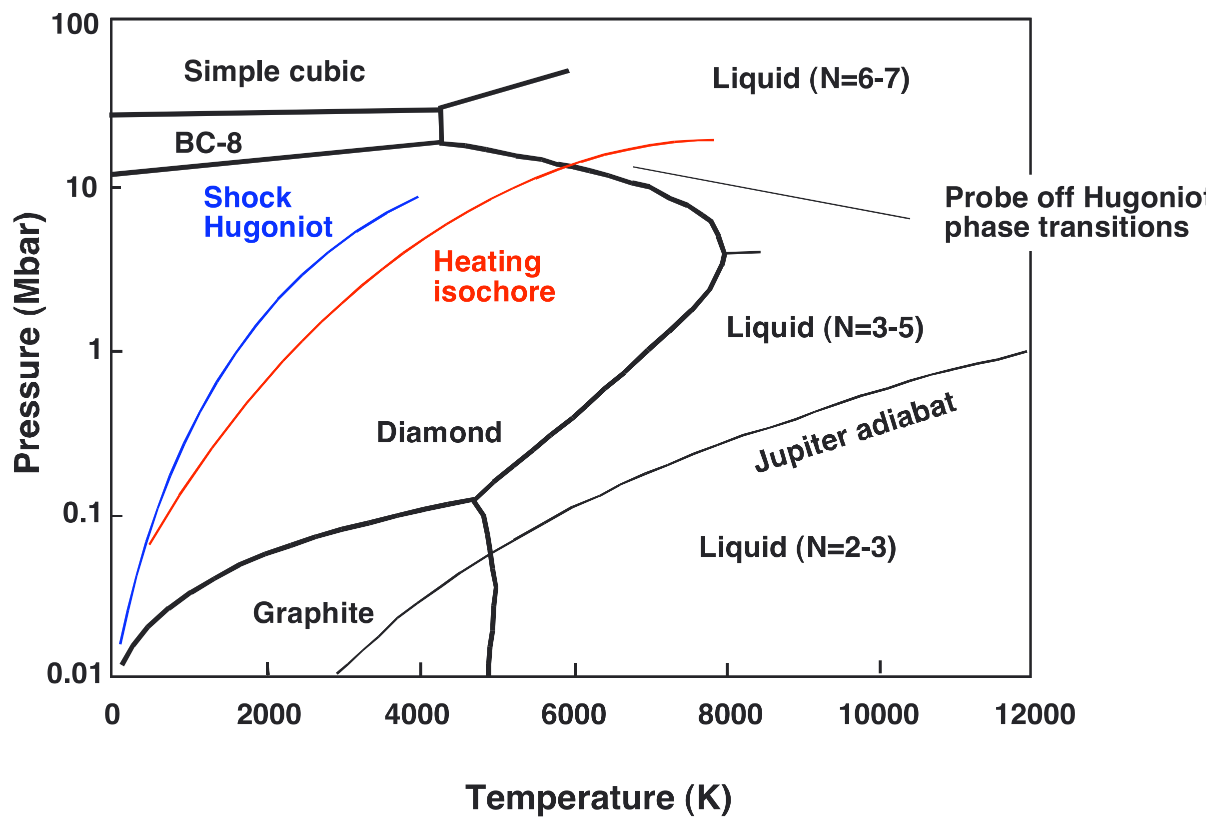


Viewgraph supplied by M. Key, LLNL

Interesting off-Hugoniot phase transitions can be probed through a combination of laser shocking and SPL isochoric heating

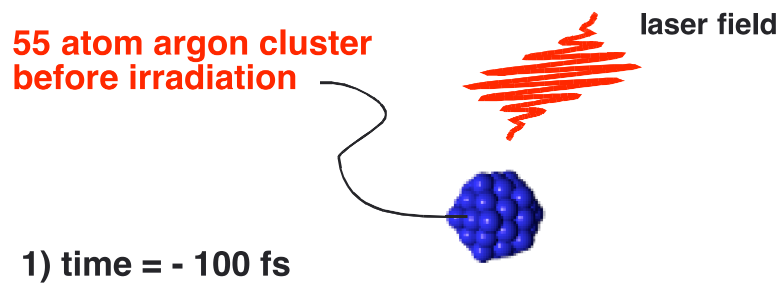


Carbon phase diagram

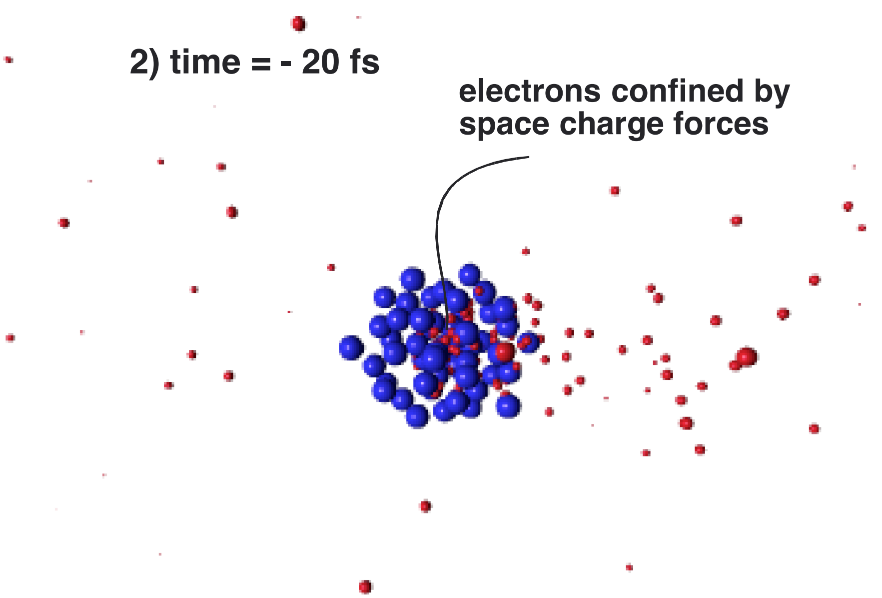


Phase diagram adapted from M. P. Grumbach, and R. M. Martin, "*Phys. Rev. B* 54, 15730 (1996)

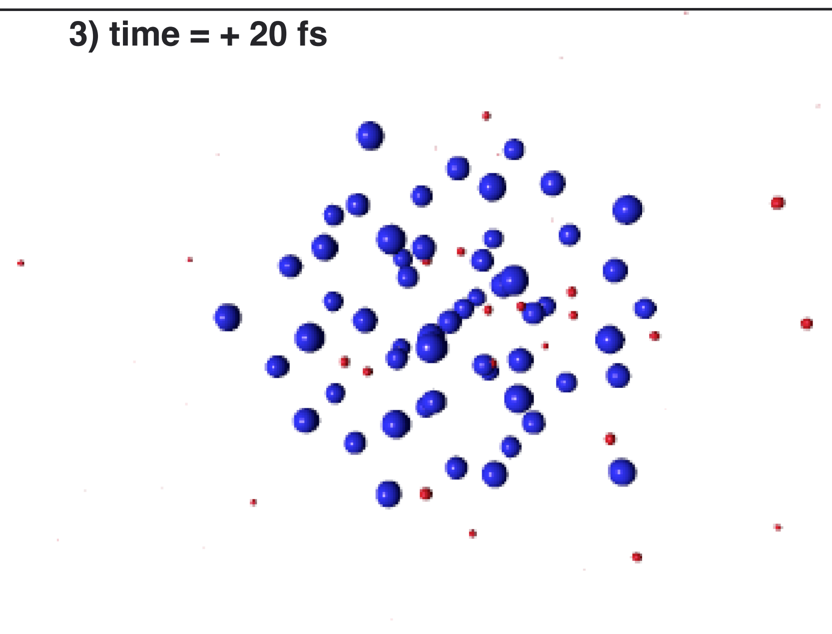
A cluster irradiated by an intense fs laser creates a microplasma which explodes after excitation



Simulation with I = 10^{16} W/cm^2
□□= 50 fs

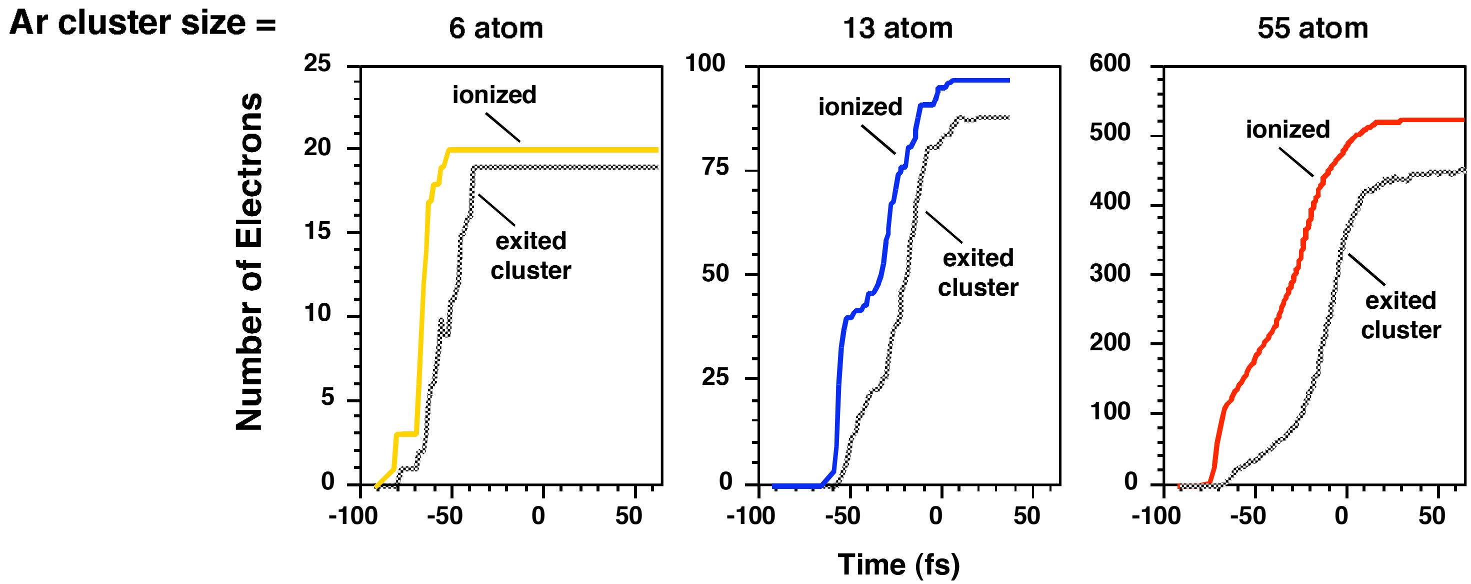


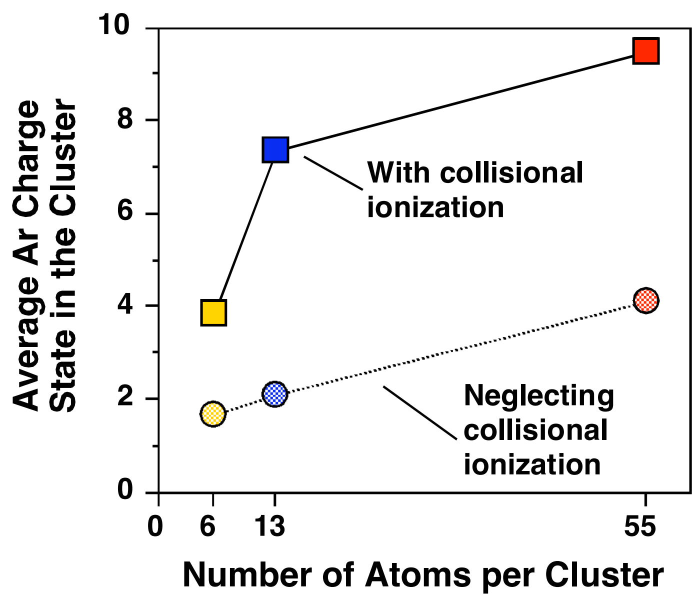
Laser field begins to heat and expel electrons from cluster

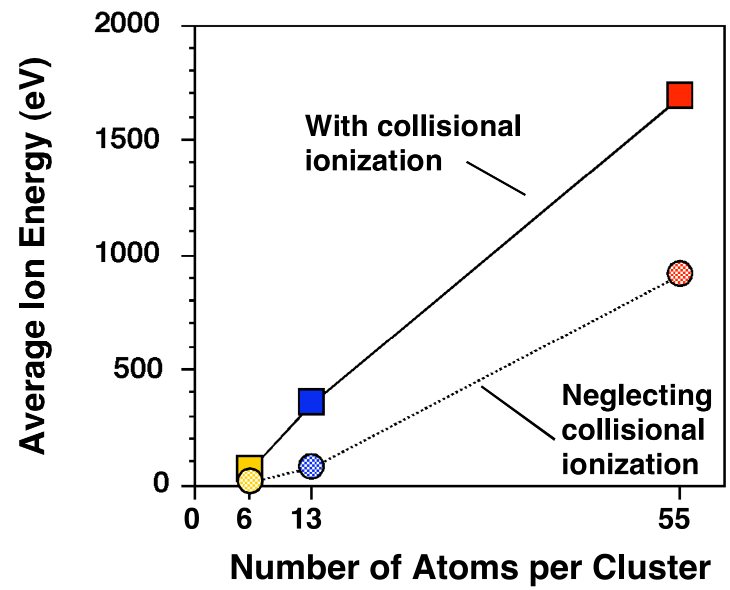


Ions explode by Coulomb forces

Simulations indicate that space-charge forces retain electrons within the cluster when the size increases

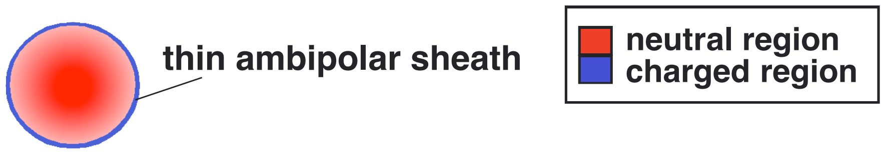






The explosion of a cluster irradiated at high intensity can often be described by one of two simple models

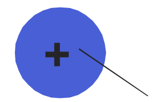
Hydrodynamic expansion



$$f(E)dE \sim E^{-1/2}\, e^{-(6E/kT_e)}$$

(asymptotic region for a spherical, isothermal expansion)

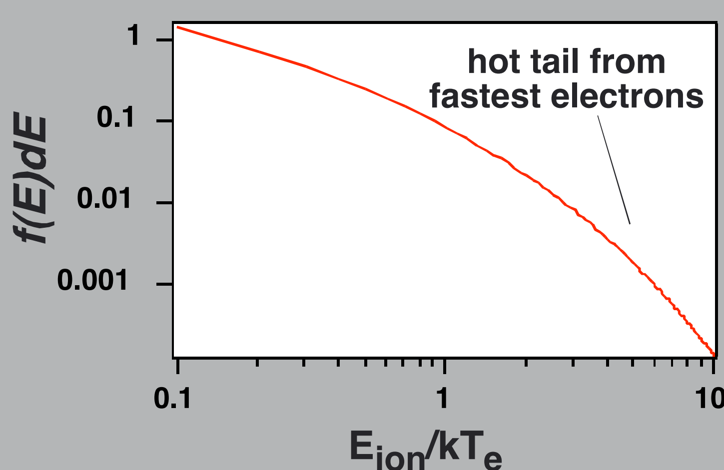
Coulomb expansion



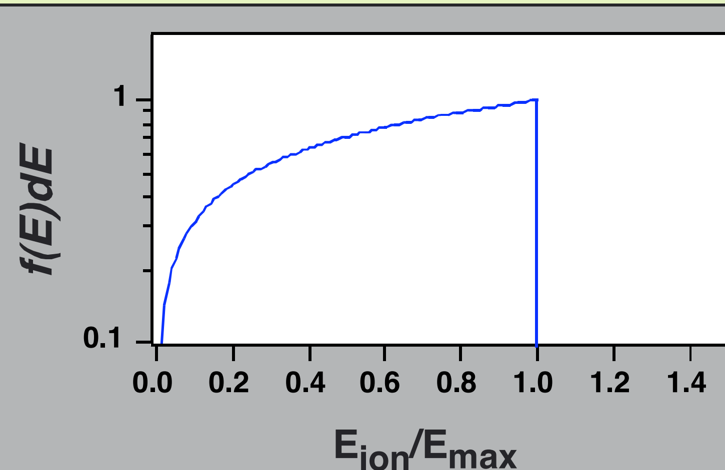
$$f(E)dE \sim E^{1/2}\, dE \qquad E<E_{max}$$

$$E_{max} = (ne^2/3\varepsilon_0)\, r^2$$

Hydro expansion reflects electron energy distribution



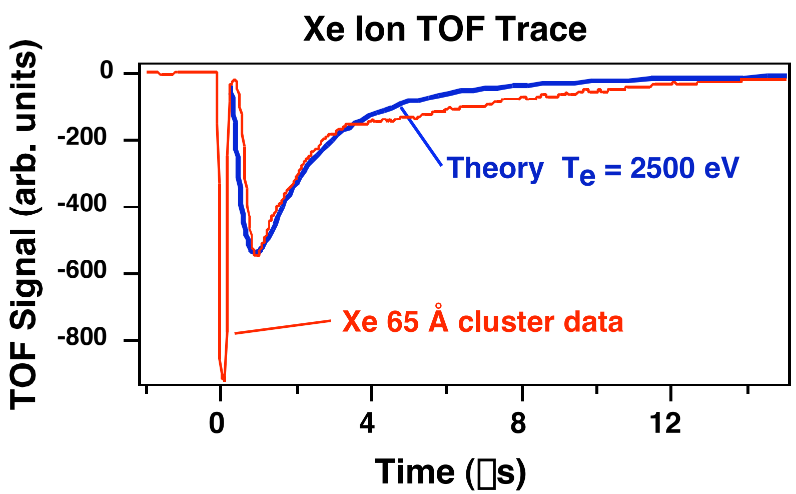
Coulomb expansion reflects only the ion spatial distribution

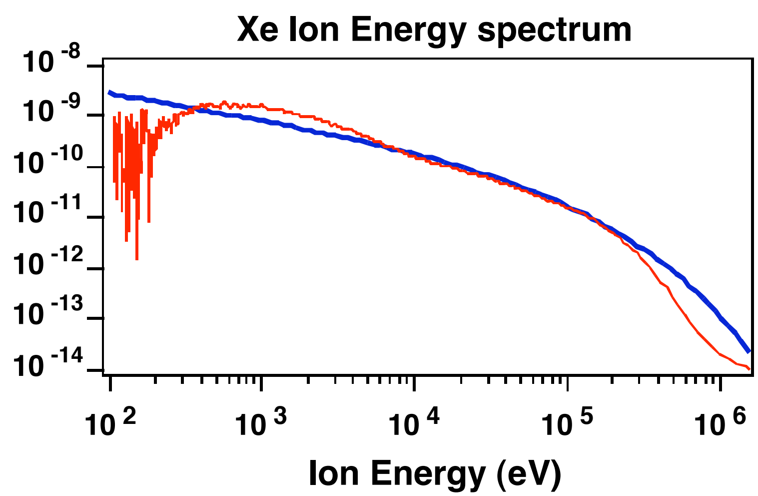


The measured ion energy spectrum of Xe clusters is consistent with the hydrodynamic expansion of a plasma into vacuum

Comparison of Theoretical and Experimental Ion TOF and Ion Spectrum

Xe average cluster size:
65 Å ±5 Å (~ 2500 atoms)
Peak laser intensity:
2 x 10^{16} W/cm^2



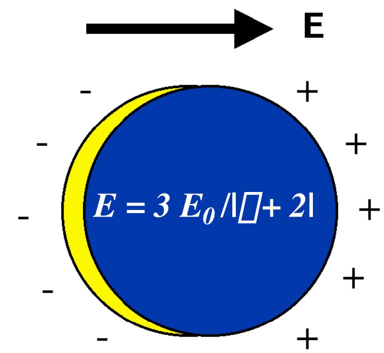


The theoretical curves represent the self similar solution of an isothermal electron driven plasma expansion into vacuum

This comparison suggests that the cluster explosion is more closely akin to the free expansion of a plasma and is unlike the Coulomb explosion of small molecules

Collective behavior of the confined electron cloud is important in the laser cluster interaction

We can calculate the natural frequency of a cluster by looking at the response when two solid charge spheres are displaced a small distance x and released

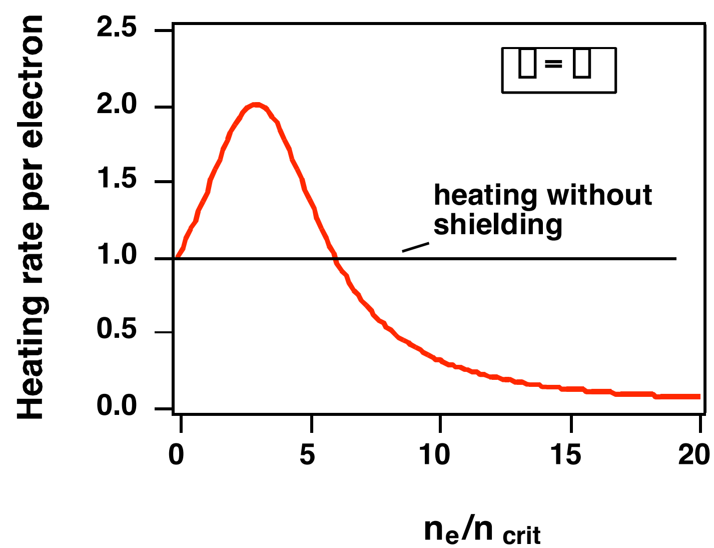


$$E_x = \frac{4\pi e n_e}{3} x$$

$$\frac{d^2x}{dt^2} + \frac{4\pi e^2 n_e}{3m_e} x = 0$$

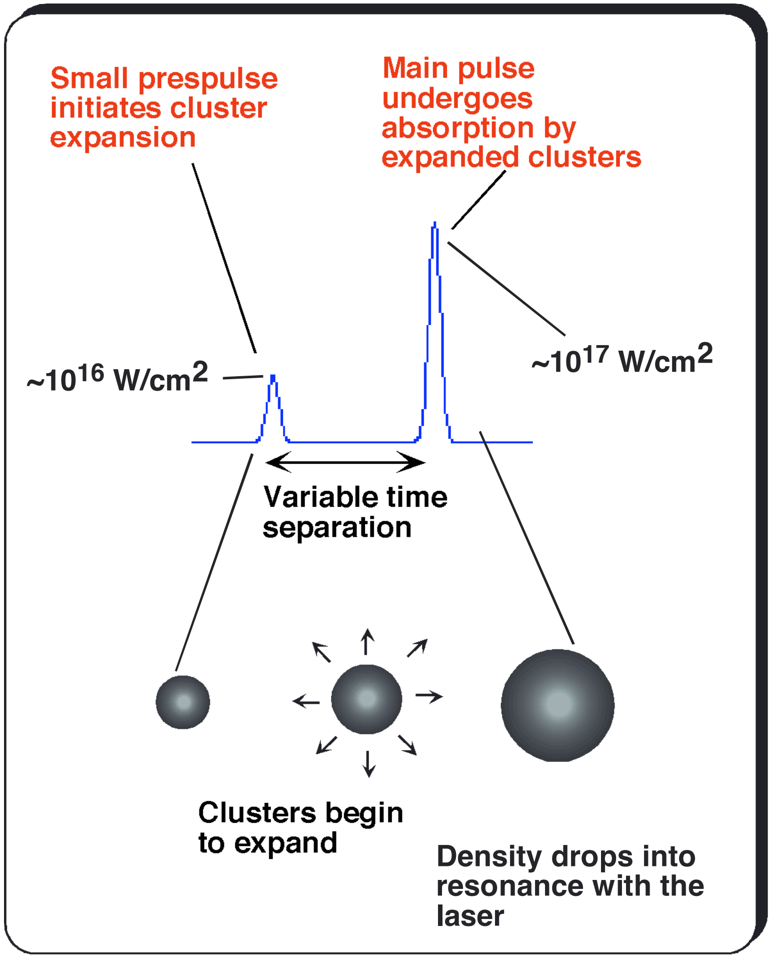
The solutions to this equation are oscillatory with frequency

$$\boxed{\omega_{cp} = \sqrt{\frac{4\pi n_e e^2}{3m_e}} = \frac{\omega_p}{\sqrt{3}}}$$

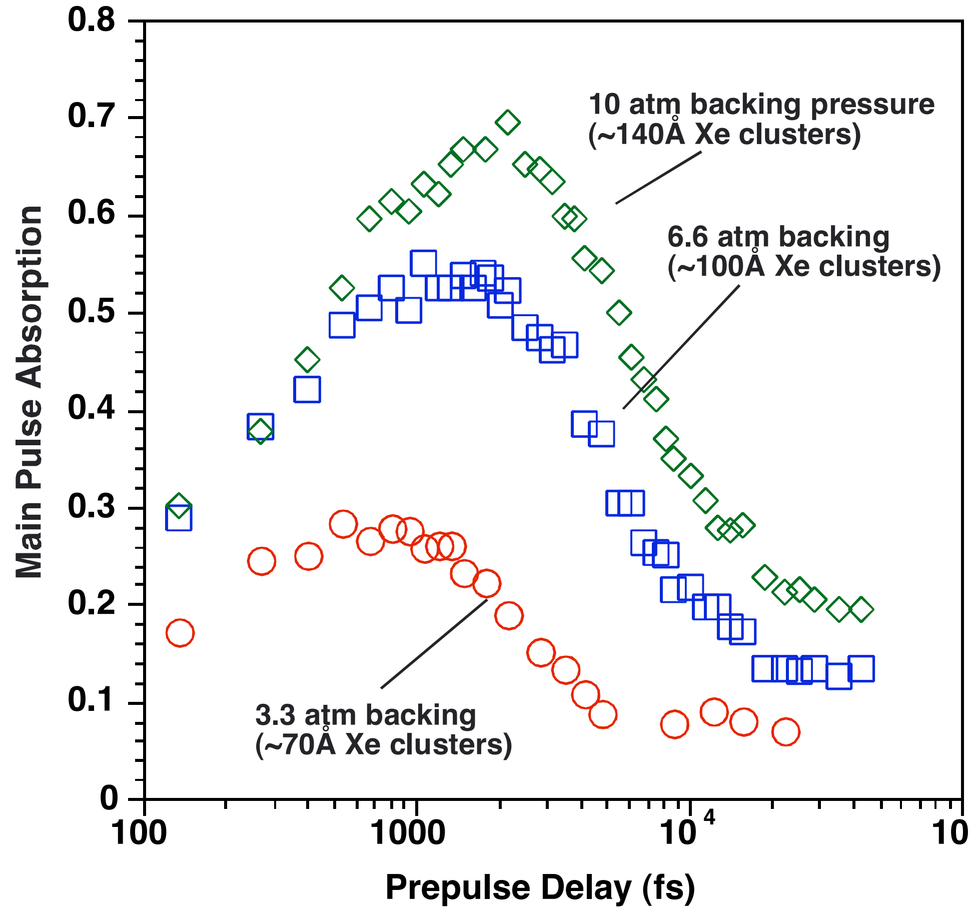


The cluster microplasma exhibits a "giant resonance" akin to the giant resonance in nuclear physics

Time resolved absorption measurements in expanding clusters suggest the presence of a resonance



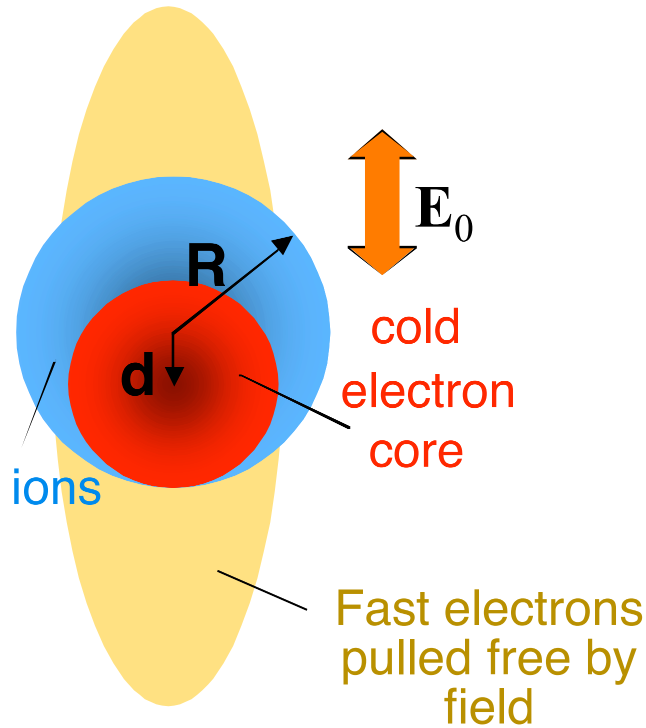
Short Pulse Energy Absorption in a Xe Cluster Medium as a Function of Pre-pulse delay



We have developed a model to treat a cluster in the regime between the Coulomb and Hydro models

Model elements

- Extracted electrons escape if $\square = \frac{eE_0}{m\square^2} >> R$
- The remaining electrons form a cold conducting core
- The core displacement adjusts instantaneously to the laser field (ie $\square_p$>>$\square$)

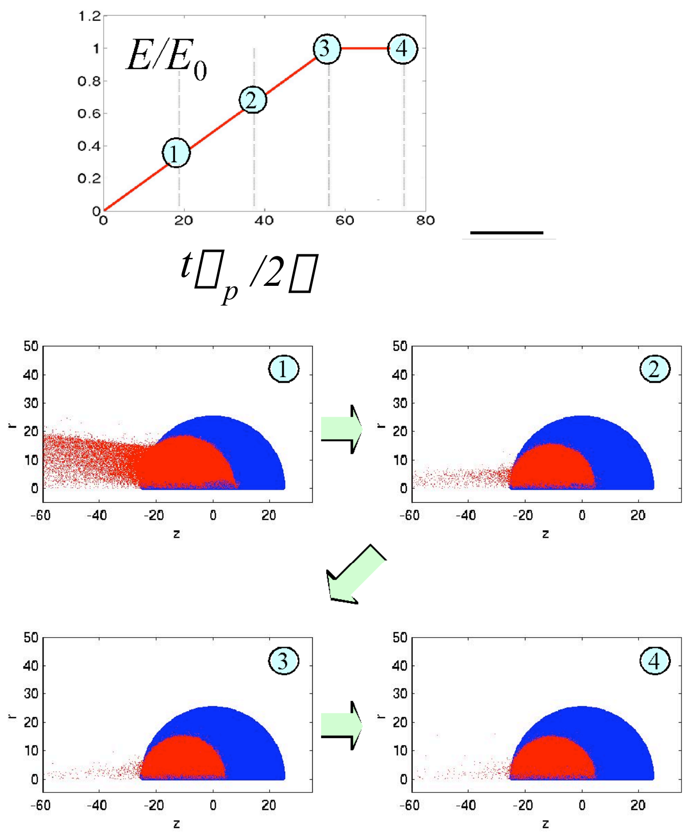


Model predictions

- A cold electron quasi neutral core forms inside the ion sphere and oscillates with the laser field
- An anisotropic space charge field will drive the cluster expansion

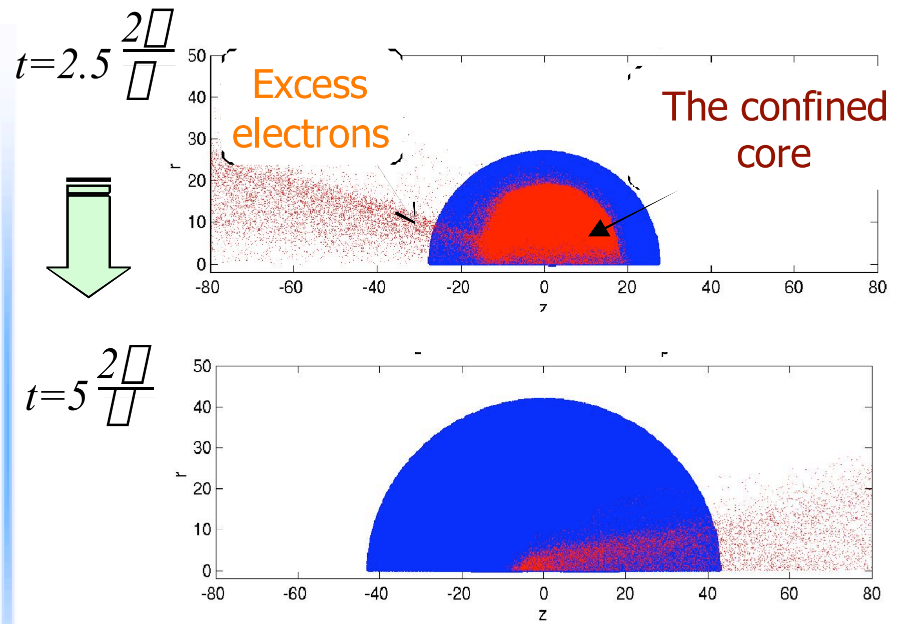
2D PIC simulations show a cold electron cloud in the irradiated cluster and an ejected stream of electrons

Electron core formation and electron leakage due to ion expansion



- Monotonically increasing field extracts electrons as the core contracts (1 → 3)
- No contraction in constant field (3 → 4)

Simulation with oscillating field and mobile ions



- Ion expansion reduces the potential well for the electron core
- The excess electrons leak out of the well and leave the cluster

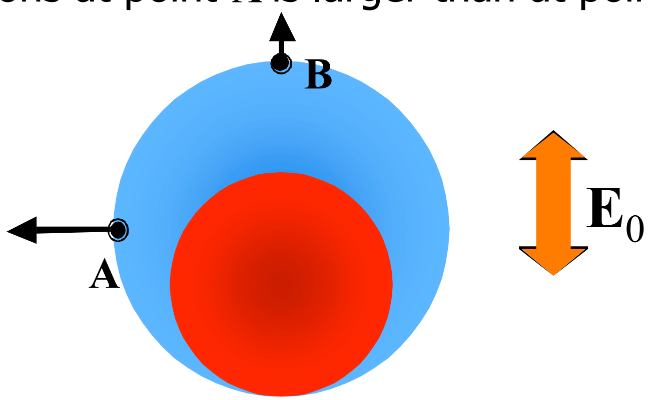
This model predicts an anisotropy in the cluster explosion with a preferential axis for ion ejection

Ion expansion anisotropy

High Field Limit

$$\xi = eE_0/m\omega^2 >> R$$

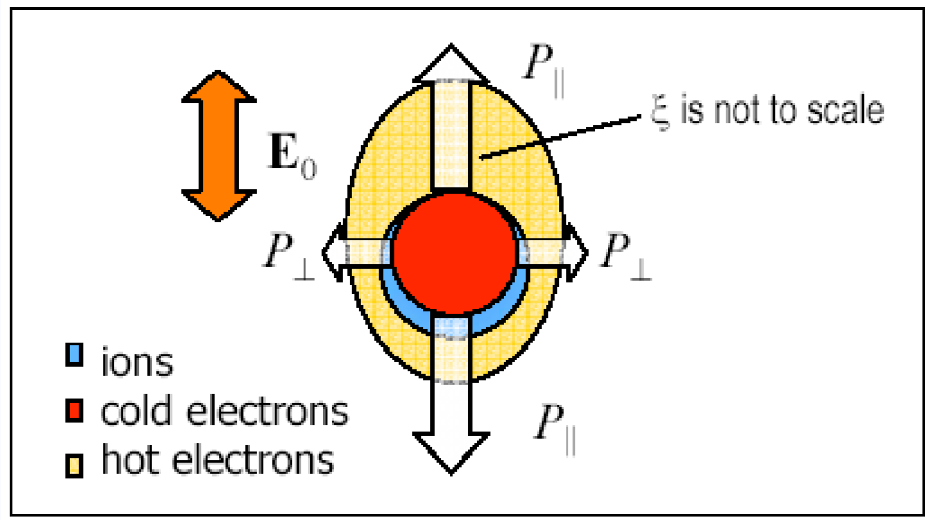
- Electrostatic space-charge field (averaged over the electron core oscillations) is anisotropic
- The average accelerating force for the ions at point **A** is larger than at point **B**



Ions expand predominantly across the laser field

Weak Field Limit

$$\xi = eE_0/m\omega^2 << R$$

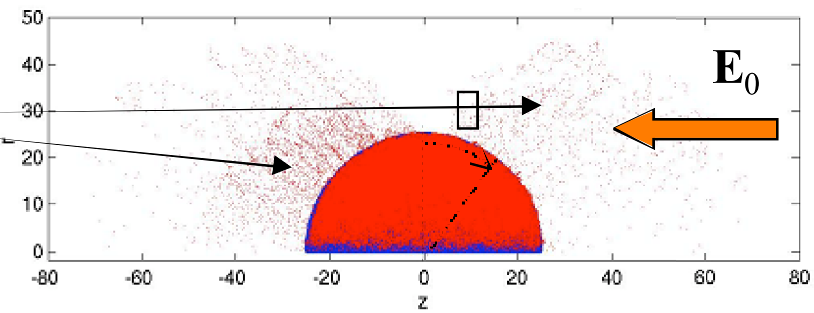


Hot electron pressure is anisotropic with $P_{\parallel} > P_{\perp}$. The electrons pull the ions primarily along the laser field.

The predicted anisotropy in ion explosion is observed in the 2D PIC simulation

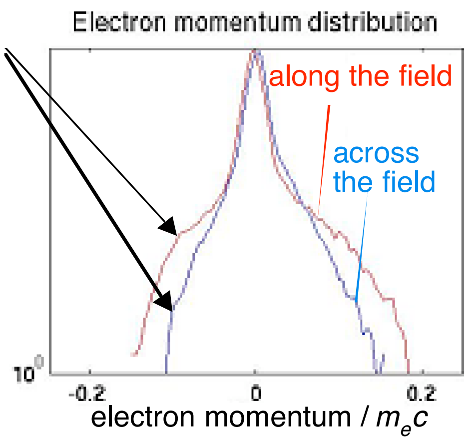
Electron heating and anisotropic ion expansion

Extracted electrons undergo vacuum heating



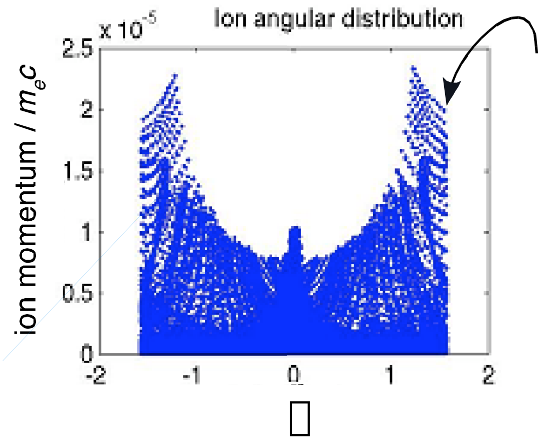
Vacuum heating produces electron pressure anisotropy

$P_{\parallel} > P_{\perp}$



Pulled by heated electrons, ions gain larger momentum along the laser field

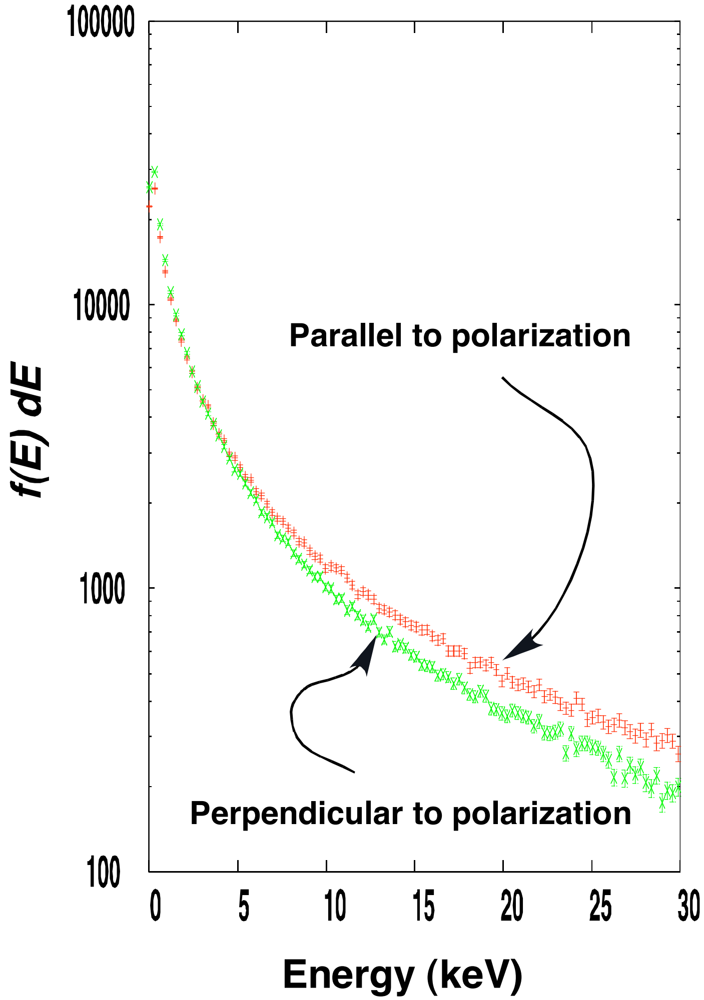
Each point corresponds to an ion

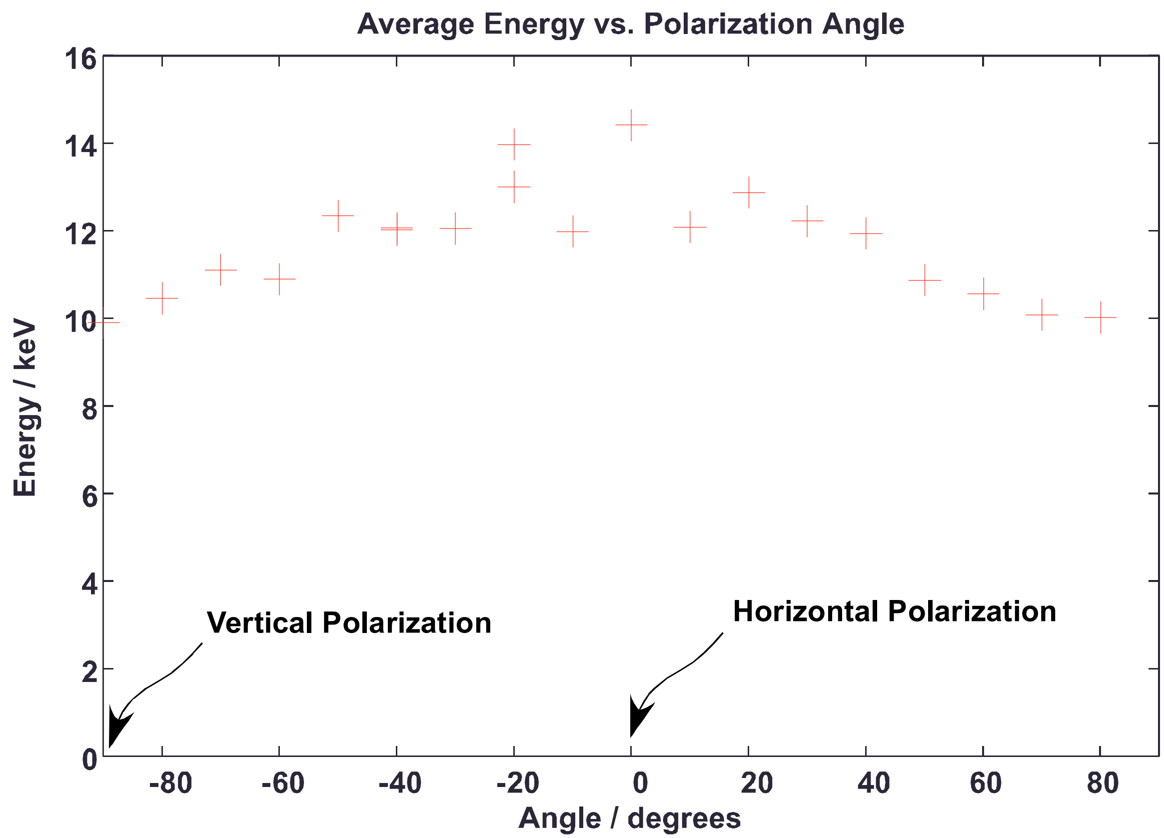


We observe a slight enhancement in ion energies along the laser polarization in exploding Ar clusters

Argon clusters

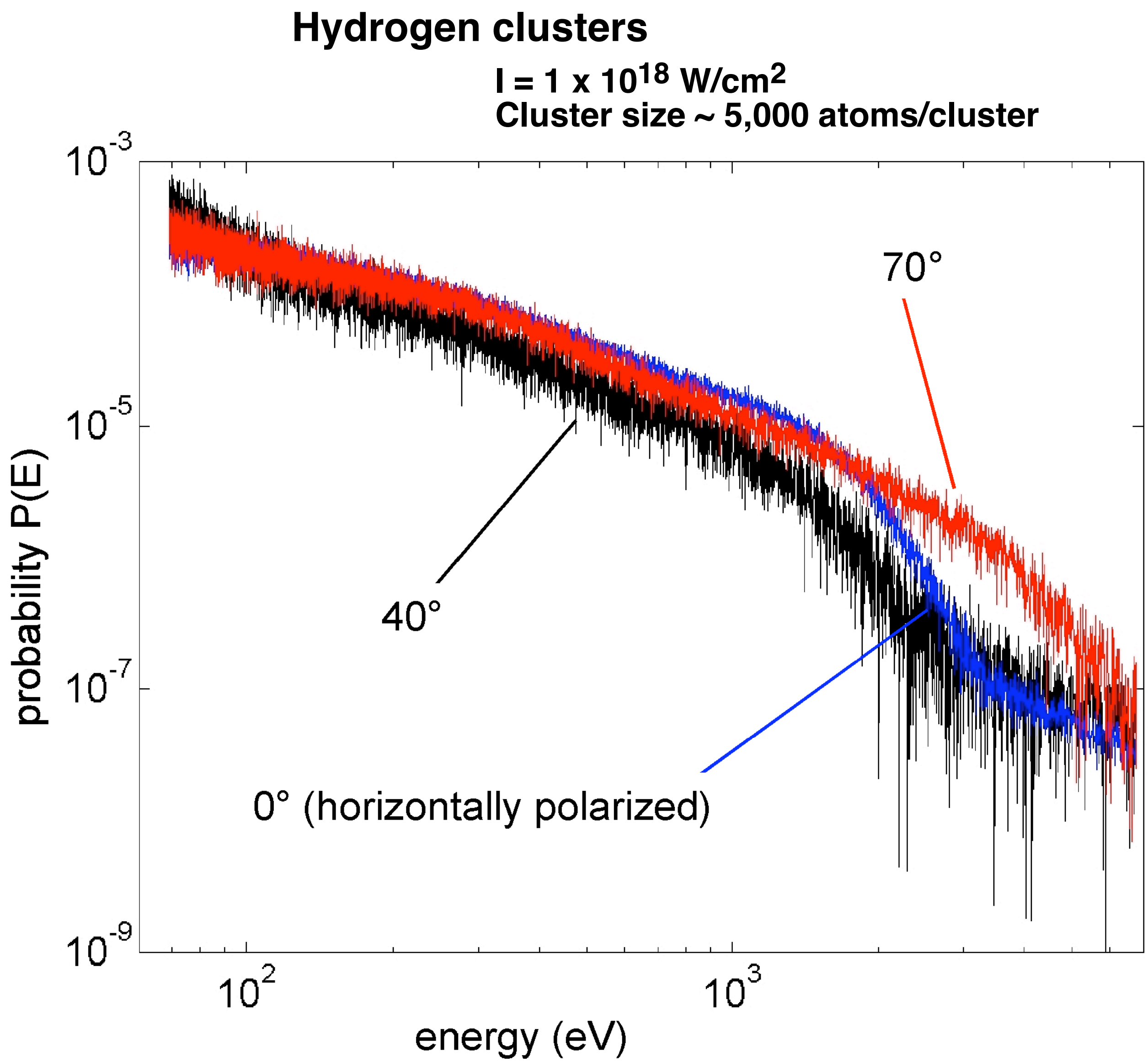
I = 1 x 10^{17} W/cm^2
Cluster size ~ 30,000 atoms/cluster





In these experiments:
Quiver amplitude ≈ Cluster size ≈ 10 nm

We observe a slight hardening in the ion energy spectrum *perpendicular* to the polarization in exploding H_2 clusters



Conclusions

• Short pulse lasers have the potential to study warm and hot dense matter in unique regimes

• Bulk heating mechanisms with higher power lasers will likely be needed for quantitative information

• X-ray or fast proton heating with laser produced radiation sources may represent a means for isochoric heating of thick layers

• Clusters represent an interesting medium for study of high density, non equilibrium plasmas